Mixed and pure forest plantations in the tropics and subtropics

Based on the work of
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FOREWORD

"Plantation forests represent approximately 3% of the present forest area but contribute a much higher proportion of the annual world production of wood"[1]. In several countries in the tropics these plantations have been the primary source of wood products and in others have even been seen as alternative sources of supply to the natural forest, which they thus protect from over-exploitation. Plantations are also established to provide shelter for livestock and to prevent erosion by wind or water, and to provide a range of non-wood forest products. Recently there have been proposals to create plantations to act as "carbon sinks" with the aim of reducing global warming caused by the greenhouse effect. The objectives of plantations were summarised in one of the recommendations of the 10th World Forestry Congress: "A large increase in the area of plantations is an absolute necessity, in order to satisfy a growing demand for wood products, to reduce stress on natural forest ecosystems and to sequester atmospheric carbon".

Yet forest plantations have attracted criticism, despite their potential benefits. The rapid expansion of industrial plantations in the last forty years has led at times to strongly adverse reactions. These plantations have been overwhelmingly composed of only a few species on any scheme, and generally of a single, even-aged species in a compartment. Sometimes, in creating these plantations, the rights of access of local people to the site have been lost, or species have been replaced on which they depended for some aspect of their daily lives; often the clearing of the land and the burning of debris have caused erosion. To many people the appearance of such plantations, even in maturity, is artificial. Some temperate countries have claimed that stream flow is acidified in certain situations; some other countries have suspected that site productivity has been reduced in second or subsequent rotations. The most apparent cause of these problems is the perceived unnatural composition and structure of the large, even-aged blocks of one or a few species, and the apparent solution seems at first sight to be to plant a mixture of many species and ages.

A similar situation of criticism on the one hand and large potential benefits on the other arose with increasing emphasis on the use of species of the genus *Eucalyptus*. The Swedish International Development Agency (SIDA) commissioned FAO in 1985 to prepare a study[2] to review the available information on the ecological effects of *Eucalyptus* plantations which provided an authoritative report on the state of knowledge at that time. The present study and extensive annotated bibliography has been commissioned by the Swedish Agency for Research Cooperation within Developing Countries (SAREC) with the aim of objectively analyzing the available evidence for or against the establishment of plantations composed of several species compared with those composed of one species.

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[1] The Paris Declaration. Tenth World Forestry Congress, Paris. 17th to 26th September, 1991.

[2] "The ecological effects of Eucalyptus" by M.E.D.Poore and C.Fries. FAO Forestry Paper 59. 1985.

FAO is indebted to Mr. T. J. Wormald, who had overall responsibility for drafting the study, and to Mr J. Cedergren and Ms F. Goulet who did most of the literature research; to Messrs G. B. Applegate, C. Cossalter, R. Delmastro, S. T. Mok, F. Owino, A. Persson and J. L. Whitmore who with many more from around the world provided helpful comment on the first draft; and for the bibliographic assistance of the Director, Librarian and Staff of the Oxford Forestry Institute (OFI, UK) and the Director and Staff of the Centre Technique Forestier Tropical (CTFT, France), which proved invaluable. Within FAO the study was coordinated by J. B. Ball, with inputs from G. S. Child, W. M. Ciesla, S. Darroze, K. Janz, C. Palmberg-Lerche, W. A. Rodgers, P. Vantomme and P. A. Wardle.

It is hoped that this study will be useful to foresters and others involved in forestry development in the tropics and sub-tropics, to assist them to decide on a sound technical and economic basis the species composition of forest plantations and to put in proportion those dogmatic or emotional statements in favour or against single or multiple species plantations.

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1. INTRODUCTION.

Background

The total area of forest plantations in the world was estimated in 1980 to be about 100 million hectares of which about 35 million ha were in developing countries; about 10 million ha were in tropical countries which were establishing new plantations at the rate of about 1.1 million ha yearly (Lanly, 1982, FAO, 1988). While this rate of afforestation and reforestation was only a small proportion of that in the sub-tropical and temperate zones it seems likely to increase as many countries seek to compensate for the loss of natural forests. Due to the high potential yields from plantations in the tropics (and sub-tropics) their contribution to wood production should be proportionately much greater than their area. About 40% of the existing and planned plantations have been established for fuelwood production and other non-industrial purposes (Lanly, 1982) but the rest have been for the production of industrial roundwood. These latter plantations are typically simple in both structure and species composition; it has been pointed out (Evans, 1982) that pioneers such as *Eucalyptus* species, pines and teak account for 85% of all forest plantations in the tropics.

Despite the undoubted benefits of industrial roundwood plantations, such monospecific plantations and especially monocultures - the succession of one pure stand by another of the same species - carry risks of catastrophes such as wind blow and loss from pests and disease and the likelihood of soil degradation and decline in yields. With the accelerating destruction of natural forests in the tropics there are increased fears that the forest plantation programme may be contributing to the process of environmental degradation. Nevertheless in the developing countries the heavy investment in forestry plantations that started in the early years of the century and which increased dramatically in the nineteen fifties has relied to a large extent on monospecific, short rotation plantations. Although the investment has been large in relation to previous work, in fact the total achievement is small in comparison to the predicted demand for industrial roundwood. Rotations are commonly 20 to 30 years, are seldom longer than 60 years and may be as short as 5 or 6 years (for example *Eucalyptus globulus* coppice in Ethiopia; *Albizia falcataria*[1] in Sabah, East Malaysia, *Eucalyptus* species in Brazil). Second rotation plantations are common and on some sites third rotation crops have been established. As a result of advances in tree breeding and in silvicultural techniques the potential exists for increased yields; vegetative propagation techniques make a quick consolidation of these gains possible. But if care is not taken there is also a risk that these techniques will lead to a reduction in the genetic diversity available for use and improvement. The question needs to be asked whether these developments towards more intensive plantation operations carry unacceptable risks.

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[1] Previously known as *Albizia falcata* and as *A. moluccana* and now known as *Paraserianthes falcataria*. Since the name *Albizia falcataria* is better known to foresters it has been used throughout this study.

Objectives of the study

The objectives of this study are to:

- review and analyse the benefits and drawbacks of mixed and pure plantations in the tropics and sub-tropics,
- to collate the field experiences of mixed and pure plantings,
- to determine, if possible, principles to be followed in establishing plantations,
- to suggest guidelines for field foresters and decision-makers.

This study has been derived from an extensive review of the literature and from contacts with foresters worldwide. Documented references to mixed plantings in the tropics, however, are sparse and uneven, both in geographical distribution and in quality. Therefore where experience in the temperate zones has appeared to be relevant it has been used.

This paper is directed primarily to those foresters who have the responsibility for planning plantation projects and to senior field staff and decision-makers who are responsible for prescribing the detailed management of plantations. Secondarily, it is directed to policy makers who must also be aware of the limitations of pure plantations and the role of mixed plantations.

Scope of the study

The tropics are a fairly clearly defined belt spanning the equator. Whether the boundaries are set by latitude - the tropics of Cancer and Capricorn - or by the mean temperature of the coldest month (18°C), or by the difference in temperature between the coolest and warmest month (5°C) the countries covered do not change much. The growing conditions in those countries can, however, be very variable - humid rainforests, deserts, savannas and cool montane climates. The scope of this study also includes the sub-tropics, the definition of which is geographically much more vague. Experiences have been included from the Himalayas, southern Africa and Chile; experiences in south Australia have been discussed in some detail, because so much of the evidence for and against second rotation yield decline has been collected there. The literature from northern Africa was not examined in detail, nor was that from the southern United States, though some data from there have been noted where they filled a gap in the tropical experience. Evidence from temperate zones has also been used in order to supplement deficiencies in the tropical data, where considered relevant. The selection of literature has been directed towards developing countries where possible; the availability of published records has been a major influence in determining which countries have been included.

Some technical limits have been set to the study. Those tree crops usually considered to fall within the agricultural sector, such as rubber or oil palm, and even those grown under the shade of trees, such as tea, coffee or cocoa, have been excluded. Mixtures involving the more obviously agricultural crops such as occur in agroforestry systems have been excluded, because they are covered in the extensive agroforestry literature.

This is a study of forest plantations, therefore naturally regenerated mixtures have not been considered, except in so far as naturally regenerated indigenous species may contribute to diversity in artificially established stands. Enrichment planting is in concept a technique for improving natural stands and as such would be excluded from this study, but the distinction between enrichment planting and replacement planting is often a fine one. Enrichment planting is used to establish favoured species in a matrix of naturally occurring trees; such plantings can eventually through selective felling of the natural stand be converted to a pure plantation. This technique has been used to establish some of the genera in the family Meliaceae. Enrichment planting is therefore discussed briefly.

The natural regeneration of herbs and shrubs in tree plantations, whether of a single or several species, has been considered to provide some of the benefits of a mixture; these same herbs and shrubs may be referred to as "weeds", however, when they interfere with the planted trees, especially during the establishment phase.

Importance of management objectives

The need for clear objectives for plantation establishment is paramount and is stressed throughout this study. The objectives will to a large extent determine the manner in which a plantation is established and managed as well as the species used. If the primary objective is to raise a uniform product, as is usual for an industrial process, then the scope for mixed plantations may be limited. Conversely if the primary objective is to protect a sensitive site, then mixtures may be more appropriate, and many of the techniques suited to industrial production may become unacceptable. Where the site is not a limiting factor, the end product or products and the biology of the species selected will determine the appropriateness of mixed or pure plantations.

Most of the literature discusses mixtures in relation to industrial plantations. But in the developing countries a high proportion of plantations are for "non-industrial" purposes (primarily fuelwood and poles) (FAO 1988). In the Middle East all plantations have been described as non-industrial; in West Sahelian Africa over 80% are non-industrial; in several regions, including East Africa, Insular Africa (Madagascar and other islands), South East Asia from Myanmar to Vietnam, more than 50% of plantations were non-industrial in 1980.

Table 1: Areas ('000ha) of established plantations, in 1980.

	Industrial				Non industrial		Total
	Hardwoods		Softwoods				
Africa	642	(21%)	659	(22%)	1686	(56%)	2987
Asia (excl China)	2891	(55%)	592	(11%)	1759	(34%)	5242
S.America	1085	(28%)	2322	(37%)	2170	(35%)	5877
Pacific Ocean	5		78	(89%)	5	(6%)	88
Total	4623	(33%)	3651	(26%)	5620	(41%)	13894

Source: FAO 1988

A large proportion of the forestry effort in the tropics and subtropics is involved in growing products, such as fuelwood, for which uniformity of size or technical properties is not of major importance and therefore mixtures may be suitable.

It is usual for plantation projects to have more than one objective. It is readily acknowledged that in industrial plantation projects an objective should be the maintenance of site fertility. It is probably less readily recognised that the management of a protection forest will also yield forest products and a financial return and, where there is pressure on the land, it is extremely difficult to protect forests unless they can be seen to be managed and to be productive. Production, subject to good forestry practice, is an essential part of active management and can help satisfy the requirements of villagers neighbouring the forest; furthermore in many developing countries revenue is required in order to maintain protection.

Good Forestry Practice

Reference has already been made to good forestry practice and the need for it will be stressed throughout this study. Good forestry practice means the conduct of forestry operations in such a way that not only is the plantation maintained in a vigorous and healthy condition, but also that the fertility of the site is maintained in future rotations. Good forestry practice is the technical contribution to sustainable forestry development; social and economic considerations are also of major importance. The need for good forestry practice is particularly apparent at four stages in a rotation.

1. Species selection.

It is necessary to match species to site with particular reference to climate and soil; planting a species or provenance in conditions that are different from those of its natural range, that is "off-site", generally causes problems sooner or later.

2. Site clearance and establishment.

Site clearing and establishment techniques must be appropriate to the site with particular reference to the species as well as soil type, slope and rainfall intensity. Any practice that risks serious erosion or loss of fertility is not good forestry practice; the maintenance of ground cover and the minimal use of fire and of earth moving equipment during site preparation is indicated.

3. Maintenance and management.

During the establishment phase it is important to ensure that the crop gets a good start. This is usually done by enabling the crop to dominate the site as quickly as possible and is achieved by weed control and ensuring that there are adequate nutrients and moisture, for example by adding fertiliser and by mulching or maintaining ground cover.

In later phases of growth, at least for wood production, it is important to prevent stagnation. This is achieved by timely thinning when basal area current annual increment falls off. Overstocking in older plantations is a common feature of poorly managed plantations and results in almost complete lack of an understorey and herb layer.

4. Protection.

Practising good forest hygiene to control potential sources of pests and diseases.

It is not always easy to reconcile the practices recommended; for example forest hygiene or weed control may best be achieved by a hot fire during site preparation, but that may promote erosion. Decisions depend on local circumstances and if there is a conflict between the species proposed and good forestry practice then it may well indicate that the wrong species is being raised.

Good forestry practices apply both to pure and mixed plantations, but sometimes the promotion of mixed species plantations - to obtain soil coverage, or to improve soil quality through influence on microfauna and flora - is an essential part of good forestry practice, especially on environmentally sensitive sites.

Definitions of "mixture".

A classification is given in chapter 5 which considers mixtures first in terms of whether the mixture is single layered, that is a mixture of dominants, or whether it is two or more layered; secondly whether the mixture is temporary or permanent. This is a convenient classification for describing silvicultural requirements. It is also worth remembering that there is a spectrum of degrees of mixture from one extreme of "purity" to be found in a monoclonal plantations, through polyclonal plantations, monospecific (single or multiple provenances), plantations of a few species grown in blocks of one age and finally, at the other extreme, to a polyspecific all-age plantation. This spectrum also exists in nature, where natural forests may not necessarily be composed of many, or even several, species. A pure plantation is generally taken to be a monospecific crop which may consist of one or several provenances; in the tropics a mixed industrial plantation is usually a mixture of two species, but the manner of mixture may be quite varied - for instance single or multi-layered, coppice, temporary or permanent. Mixtures are not always the consequence of a deliberate planting policy, they may be created as a result of the natural regeneration of understorey "weed" species in plantations maintained at a relatively wide spacing. Polyspecific all-aged industrial plantations are not common, though the Sundapola Mahogany/Teak/Jak plantations in Sri Lanka (Tisseverasinghe and Satchithananthan 1957; Muttiah 1965, 1991) can be considered to be a small scale example. The very complex mixture approximating to a natural mixed tropical forest described above might, however, be appropriate to fuelwood plantations and would certainly be appropriate to protection plantations on sensitive sites.

The definitions of mixtures given above imply an intimate, tree by tree or line by line mixture or possibly mixtures of small groups. But a mixture, in the broad sense, can also be obtained by planting adjacent compartments or blocks with different species and a mixture of a different kind can also be achieved by rotating species. In this study all levels of mixture are considered; lessons can be learned from the techniques for achieving clonal mixtures as much as from mixtures of species or genera. In particular attention is drawn to the potential for the use of a "broad sense" mixture of blocks rather than a "narrow sense" intimate, tree by tree mixture. One of the objectives of this study is to examine how the desirable effects of mixtures can be achieved with the minimum complexity of management systems.

The extent of monospecific plantations

A recent assessment of the areas of forest plantations in the tropics shows that eucalypts, pines, teak and acacias are the most frequently planted species. In Africa and in tropical Latin America, Eucalyptus spp. and pines comprise about 50% and 80% respectively of the plantation area, whereas in tropical Asia there are a large number of species, of which the eucalypts, teak and various acacias comprise 32% (Pandey, 1992).

The extent to which pure plantations have been established in the tropics is not known, but is indicated by the following relatively small list of the major plantation species of the tropics (Evans 1987):

Pines *P.patula, P.caribaea, P.elliottii, P.kesiya, P.merkusii, P.oocarpa* & others	34%
Other conifers *Araucaria cunninghamii, A.angustifolia, Cupressus lusitanica* & others	3%
Eucalypts *E.grandis, E.camaldulensis, E.globulus, E.saligna, E.deglupta, E. tereticornis, E.robusta, E.citriodora, E.urophylla* & others	37%
Teak *Tectona grandis*	14%
Other hardwoods *Acacia, Gmelina arborea, Meliaceaea, Terminalia* spp., *Albizia* spp., *Triplochiton scleroxylon* & others	12%

This list names 10 coniferous species, 9 eucalypt species and 7 other hardwood families or genera. Given the range of soils and climates in the tropics this would appear to imply the likelihood of a still more restricted range of species in a country or in a relatively homogenous location such as a district. However, some of these species, e.g. *Eucalyptus camaldulensis* occur naturally over a very large area and have a number of different provenances.

Mixtures in the narrow sense of raising more than one species in a compartment are not common in industrial plantations. In the broader sense of establishing different species in neighbouring compartments it is hard to estimate from published records the extent to which mixing is taking place. In New Zealand *Pinus radiata* accounts for 85% of forest plantations (Burdon 1982), so clearly there is very little mixing there. In some of the states in Australia the proportion is even higher (Fergusson 1983).

Some of the pulp plantations in southern Africa may involve large blocks of *Pinus patula* or of eucalypts. The Usutu plantations in Swaziland, which cover 52 000 ha, have predominantly been established to *P.patula* as has the Viphya plateau in Malawi and the same applies to the pulp planting schemes in East Africa at Sao Hill in Tanzania and Turbo in Kenya.

It used to be the practice in many of the forest districts in the highlands of East Africa to plant a range of fast growing species such as *P.radiata, P.patula, Cupressus lusitanica* and some *Eucalyptus* species. This range, however, has been steadily eroded. The area of eucalypt planted was reduced sharply when the railways converted to oil burning, *P.radiata* ceased to be planted on any scale in the nineteen sixties because of *Dothistroma* blight and now *C.lusitanica* and other Cupressaceae are subject to severe attack by the aphid *Cinara cupressi* which may preclude them from future plantation programmes in East Africa. In Kenya softwood planting in the highlands is now largely confined to one species, *Pinus patula*.

It appears that monospecific industrial plantations are common, but there are reports of extensive plantations of mixed species (*Eucalyptus tereticornis* and *Acacia auriculiformis*) in Vietnam (Cossalter 1991) and elsewhere, though it is not clear whether these are industrial plantations nor whether they have been successful in meeting defined objectives.

2. FOREST ECOSYSTEMS.

Natural forest ecosystems vary from great complexity to comparative simplicity of species associations. Ecosystem simplification is associated with specialisation and tends to be a response to extreme climatic, edaphic or other abiotic conditions. Thus forests with simplified structures and a reduced number of specialised species are more common in the harsher climate of the colder areas of the world; the birch forests of the northern boreal forests, *Pinus mugo* and *P.cembra* at high elevations in Europe, *Cupressus sempervirens* on south-facing limestone slopes in Crete, *Alnus glutinosa* in peaty valleys in Britain (Rackham 1990). In South Australia the indigenous woodland is characterized by near monospecific stands (Boardman 1990).

Although in the humid tropics rainforests are typically polyspecific and many layered, stands having reduced diversity do occur; they include natural stands of *Eucalyptus* species and tropical pines, as well as mangrove swamps and tree savannas with low rainfall and frequent fires, both of which are relatively poor in tree species. In Uganda stands dominated by *Cynometra alexandri* and by *Parinari excelsa* are two examples of natural stands in which the number of species is limited. Elsewhere in Africa pure stands of *Acacia tortilis, A.nilotica* and *Colophospermum mopane* are not uncommon. In Latin American dry zones large areas may be covered by a single *Prosopis* spp. In the Kemahang forest in the Malay peninsular there was, before exploitation in the nineteen sixties, a reduced number of dipterocarp species and of other species in the families Burseraceae, Lauraceae, Myristaceae, Myrtaceae and Sapotaceae and which are believed to have arisen after a freak storm of November 1888 (Whitmore 1984). *Agathis* species in south Kalimantan occurred, before logging, in stands up to 5000 ha in area in which it formed the main or sole top-of-canopy species (Whitmore 1984). In many cases within polyspecific stands there may be groups of a single species, or even clumps of a single clone. Thus although, given conditions of adequate nutrient supply, plenty of moisture and high solar radiation, complex polyspecific ecosystems are normal, there is nothing inherently unnatural about monospecific stands; where natural mixtures occur, on the other hand, they are often temporary.

All natural ecosystems are dynamic and are characterised by successional phases. Disturbances occur at irregular intervals in natural forests, sometimes after centuries, but on some sites, for instance savannas prone to fire, at frequent intervals. The stages of a secondary succession after a disturbance to a forest ecosystem are typically characterised by an early invasion of a few light demanding, aggressive but short-lived pioneer species frequently occurring in single species stands, which are followed by colonisation with successively more shade tolerant species which grow up through the canopy of the preceding seral stage eventually to become dominants. Ultimately in some ecosystems in the late successional stage a relatively constant mix of species is reached, which will last until the next disturbance (Whitehead 1982), although in others especially in the temperate zones but also in moist high forest systems (see the examples from Uganda mentioned above) the climax forests may be more or less single species.

After a major disturbance to the ecosystem initial growth rates tend to be high and for some pioneer species in the early successional stages can be very high; these pioneer species are better able to respond to site fertility, but are relatively vulnerable to stress. Subsequently in the later successional stages as the biomass increases the pioneer species are replaced by more shade tolerant species, which are slower growing, but more resistant to harmful factors. Eventually the situation may be reached in late successional stages when biomass may be very high, but growth rates are negligible.

Some ecologists have argued that this final state is the ideal climax representing a stable and self sustaining condition - although as noted above it may not be very diverse in terms of tree species. Others have pointed out that it is doubtful if a true climax is ever attained (Jones 1945), because sooner or later disturbances occur. The significant point is that stability in an ecosystem is considered to be attained when there is an adequate diversity of functions. But a species can have more than one function and a function can be performed by more than one species. In industrial plantations stability is achieved when there are no major unprescribed changes in yields or production and site fertility and soil structure are maintained. Even though stability may be dependent to some extent on species diversity, it does not necessarily follow that the aim in plantation forestry should be to have as many species as possible in order to achieve maximum stability or even that greater species diversity must imply greater stability. The essential for achieving stability is that there should be enough species to achieve an adequate diversity of functions (Zwolinski 1990) and the number of species required for stability in industrial plantations will depend on the site.

The objective in growing plantations for commercial gain is frequently to take advantage of the high growth rates in the early stages of succession; in the tropics and sub-tropics increments in plantations are three to seven times those of the merchantable species in the later successional stages of the natural forest (Evans 1990), though this is a consequence of selection and tree breeding, close spacing and management as well as the utilization of initial high growth rates. The harvest is taken when, or shortly after, growth starts to slow down. The act of harvesting causes a major disturbance to the ecosystem which allows the cycle to be restarted in the fast growth phase again. In commercial plantation forestry the objective is to maintain the ecosystem in a state of controlled instability, locked in a given successional stage, but experience has shown that sustainable yields can usually only be maintained with some artificial inputs such as fertilizer, insecticides, fungicides etc. combined with sound forestry practice

If, however, the objective is protection of the site without consideration of commercial profit, then the ecosystem required is one that can provide this function, possibly but not necessarily by progress to a late successional stage. The objective will be fully met if the ecosystem can be made self-sustaining, possibly by retaining a wide range of species.

Management, aimed mainly the conservation of biological diversity, implies the retention of the maximum number of species and within-species diversity, and furthermore it requires the maintenance of all successional stages in the ecosystem. Maintaining an ecosystem, however, does not necessarily mean the conservation of all its species, and it is possible to conserve a species and lose genetically distinct populations or genes which may be of value in adaptation and future improvement of the species (Wilcox, 1982).

In plantation forestry,particularly where rotations are short, some trade offs have to be made. Gains in yields may be offset by negative factors such as the removal of nutrients in logging, a reduction in nutrient cycling ability, damage to the soil structure or a possible lowering of resistance to pests and diseases, which have to be made good if yields are to be sustained. Skill is required to determine how to minimise these losses by matching species to site and by good forestry practices and to determine where, how and when natural processes (such as the regeneration of an understorey) can and should be used and to what extent they should be supplemented artificially. Mixed planting does play a role and should be based on accurate observation of local succession, where this information is available. But if short rotation forestry is an acceptable use for a site, mixed planting by itself cannot be a panacea for the problems associated with commercial forestry. The shorter the rotation, the closer the situation approaches to that of an agricultural crop and the greater becomes the importance of soil fertility (Lundgren 1980) and the more likely that fertilizers will have to be added.

3. ENVIRONMENTAL IMPACT.

3.1 SOILS

One of the major concerns expressed concerning the risk of creating monospecific plantations is that they cause a loss of fertility and soil degradation. The main features of soils on which afforestation in the tropics and subtropics mostly takes place and the interaction between tree crops and the soil is discussed in detail in Appendix II.

Soil characteristics

Soils available for afforestation in the tropics and sub-tropics are often intensely weathered and frequently deficient in nutrients, but even when they are less weathered they are liable to loss of nutrients through leaching. In the wet tropics these soils can support a heavy biomass by virtue of the rapid decomposition of the litter and mineralization of nutrients in the topmost layers of the soil. On clearing the vegetation for agricultural crops or for establishing tree crops there is a high risk of loss of organic matter, leaching and the loss of this fertility. It is important that these sensitive sites are not cleared; on sites that have become badly degraded the first priority must be to re-establish the organic matter content of the soil. In the arid and semi-arid zones the litter layer and organic content of the soil may be further depleted by fires and as a result the natural climax tree species tend to be fire resistant, but the sites only carry a low stocking because they are infertile.

The ability of trees to take up nutrients is determined not only by their availability in the topsoil but also by soil moisture and the soil structure. The requirements for each nutrient vary with the stage of development of the stand; it tends to be at a maximum immediately after crown closure in plantations. For some nutrients, phosphate in particular, the rate of release from mineral soil is slow. The quantity in solution available at any one time for use by the trees is very small in comparison with the annual requirement of the trees and with the quantities locked up in the tree biomass and in the litter on the forest floor. In these conditions healthy, vigorous growth is dependent on rapid decomposition of the litter to maintain the nutrient cycle.

The process of decomposition is closely associated with the activities of the soil microfauna and flora. The function of soil microfauna and flora have not been studied in the tropics and sub-tropics as closely as they have been in the temperate zones. But it is clear that microfauna fragment and in some instances (for example termites) mineralize litter; the process is completed by fungi and more particularly by bacteria. The mixture of species composing a stand, by influencing both the proportion of cellulose and protein in the litter and the soil acidity, can be of great significance in affecting the populations of the soil microfauna and flora and their performance and a change in the composition of the leaf litter may favour one component of the microflora at the expense of another.

Some symbiotic fungi can not only exist in association with one species in a mixture, but can also benefit other components of a stand; for example in Britain *Suillus variegatus* on *Pinus sylvestris* can make available nutrients which can be used by *Picea abies* (Ryan and Alexander 1990). In Swaziland it has been found that at higher altitudes considerable quantities of needle litter can build up under *Pinus patula* maintained at a close spacing (Morris 1986); in these circumstances the form and numbers of mycorrhizae may change (Robinson 1973). It is observable that the problem of litter accumulation is particularly acute in close canopy softwood conifer stands in the tropics and sub-tropics, but is less of a problem in open stands having an understorey of broadleaf species; in effect the mixture of species provided by the understorey promotes the breakdown of forest floor litter.

Concern has been expressed at the effect on the soil of close planting of pure stands of teak. The problem is that teak is deciduous and the leaves, which do not readily decompose, are highly inflammable; as a result fires are frequent in teak plantations on sites having a pronounced dry season and in consequence the forest floor in plantations is frequently bare at the start of the rains. Additionally the leaves of teak are large and the drip from the leaves on the tree intensifies the erosive effect. Planting teak at wider spacing and either planting a mixture of other species with more easily decomposed and less inflammable leaves or allowing shrub or herb species to come in as an understorey reduces the incidence of fire and erosion (Bell 1963).

Though most of the nutrients in the topsoil are derived from minerals in the subsoil or from litter, some nutrients are accumulated in the topsoil from the atmosphere. Nitrogen fixation in the roots of some plants is an example of this process. This process is chiefly associated with legumes, but fixation of nitrogen can occur in over 200 species from 20 genera (Bond 1983), of which *Casuarina* is probably the most significant non-legume tropical tree. Nitrogen fixation can operate as a direct transfer from the root nodules to the soil, but the most common pathway appears to be through the leaf litter (Ewel 1986). In Hawaii the nitrogen fixing effect of *Albizia falcataria* on soil nitrogen levels was much greater than that of *Acacia melanoxylon* (DeBell et al 1985), which may be because *A.falcataria* has a much smaller and more easily decomposed leaf. It should be noted, however, that the very favourable effects of mixing *Albizia falcataria* with *Eucalyptus saligna* in Hawaii (DeBell et al 1985; 1987; 1989) was achieved on old sugar cane fields, where past fertilizing regimes and the nutrient demands of the sugar cane crop may have resulted in unique soil nutrient conditions.

For nitrogen fixing plants to make a positive contribution to stand growth the site conditions must be suitable; that is there must not only be a deficiency of nitrogen but other nutrients, especially phosphate, and moisture (Sprent 1985) must also not be limiting. On sites where nitrogen is not deficient it has been shown that an admixture of nitrogen fixing trees does not enhance growth of the main species and may even inhibit it through competition for light, moisture or other nutrients (Binkley 1983; 1984; 1990). It is possible that nitrogen fixing trees are only effective when they are dominants or codominants (Binkley 1990), so there is doubt concerning the effectiveness of nitrogen fixing species grown as an understorey. It therefore appears that there is a comparatively narrow range of conditions in which nitrogen fixing plants will enhance stand growth. The beneficial effects of mixtures with nitrogen fixing trees, such as acacias in pine stands, are not always apparent (Turvey et al 1984).

Evidence for changes in site parameters reflected in second rotation yield decline

The species composition of a natural stand or of a plantation have a strong influence on the site, and particularly on soil properties. A plantation of a single species may alter the nutrient status or the physical properties of a soil from its original state under natural forest; this change may reduce both the actual and potential productivity of the site as well as the composition of the understorey or undergrowth. On the other hand a plantation of a single species may have a positive effect on the soil if it is established where there was no cover. If therefore there are changes in site properties these may be expected to be reflected in differences in growth and yield in the second and subsequent generations from the first - although such changes could be the result of different management practices or different seed as well as the result of a change in species composition or of a shift to a single species.

The concern over the possibility of second (and subsequent) rotation decline is chiefly based on two experiences, that of spruce (*Picea abies*) in Central Europe and specifically in Saxony, starting in the middle of the nineteenth century, and that of *Pinus radiata* in South Australia in the middle of the twentieth century. In addition detailed growth records from Permanent Sample Plots, which now span three rotations, have been maintained in the Usutu plantations in Swaziland. In order to understand the phenomenon of second rotation decline it is worth examining these experiences in some detail.

(a) Spruce in Saxony.

Spruce was planted in central Europe on a large scale in pure blocks from the middle of the eighteenth century partly because decline was thought to have been detected in the beech and oak forests. Spruce had always been grown satisfactorily as a pure crop on the higher elevation podsols and indeed occurs naturally in pure stands, but by the middle of the nineteenth century a decline in yields was observed in particular on the lowland clay soils. This decline in yield was attributed to the repeated establishment of pure spruce stands. In the nineteen twenties Wiedemann made extensive investigations into the problem in Saxony (summarised in Jones 1965). Partly because the analytic procedures available at the time were inadequate he was never able to pinpoint the cause of the problem. He did note that not all spruce plantations were affected, that in some the growth was checked but it later recovered and that there was some correlation with dry summers. As a result of his and subsequent work some of the confounding factors have been identified and possible causes of the problem suggested. These include

- on clay soils the spruce is very shallow rooting; in the first rotation it can often make use of old root lines, but by the second rotation these have silted up and the spruce is rooted almost entirely in the humus layer which dries out in droughts and may become water-logged in winter.
- much of the planting was on old arable land or cultivated plots in the forest - *waldfeldbau*; spruce is notoriously susceptible to the root rot

Fomes annosus[1] in these circumstances, but it takes up to a rotation for the effects of the fungus to become apparent since it enters through freshly-cut stumps and then through root grafts to living trees. Hence what was in fact a problem of the first rotation was only manifested in the second rotation.

- the soils on many of the sites had already been impoverished before the spruce was established as a result of the prevailing custom of collecting all the litter beneath the previous stands.
- management practices at the time favoured very dense stands which tended to cause an accumulation of litter which in turn impaired nitrogen mineralization.

Thus there is a range of possible explanations, which taken together could account to a great extent for the check in growth. A point of significance is that the problem was most apparent where spruce was planted off its natural site on the lowland clay soils. Unfortunately there has tended to be an uncritical acceptance of the initial explanation that attributed the phenomenon of spruce check to the use of monocultures. In fact this explanation connected unrelated events as cause and effect which has led to pure spruce frequently being equated to a pure crop of any conifer and even to a pure crop of any species (Jones 1965).

More recently it has been claimed that for middle age classes of *Picea abies* in Germany, despite the occurrence of needle loss and crown decline, yields are 20% to 40% higher than anticipated; this has been attributed to increased temperature, increased rainfall and CO_2 and higher mineralization (Kenk 1990b).

(b) *Pinus radiata* in South Australia.

P.radiata had been planted on infertile sandy soils in South Australia. The first rotation was felled at about 25 years of age and produced reasonable yields. When the second rotation was about ten years old it became apparent from the analysis of permanent sample plots that the plantations had dropped one or two and sometimes even three Site Quality (SQ) Classes (Keeves 1966). Each quality class represented 140 m^3/ha at rotation age; SQ VII had a standing volume of about 5 000 ft^3/ac (350 m^3/ha) and SQ IV 11 000 ft^3/ac (770 m^3/ha). This was therefore a serious loss. There was some indication that yield decline had not occurred in stands where slash arising from clear felling had not been burnt and natural regeneration had taken place. Burning before replanting was normal practice.

Over the next two decades research was directed to the decline in yield. The soils are coarse sands of poor water holding capacity, from which nutrients are easily leached. It was found that particular attention needed to be paid to the interaction between water availability and nutrient supply. The maintenance of the organic matter content of the topsoil was crucial to this relationship (Sands 1983). Not only did organic matter increase nitrogen availability and the cation exchange capacity, but it also reduced bulk density and increased the field capacity; in the absence of sufficient water the trees were unable to make use of nutrients even when they were available (Boardman 1982). Second rotation yield decline was thus associated with low

[1] More correctly *Heterobasidion annosum* but generally recognised by foresters under its old name.

nutrient status, low moisture availability and loss of organic matter from the soil as well as soil compaction and weed competition (Turner 1983; Squire 1983).

The solution to the problem lay in good forestry practice, that is, the preparation of the site with more care, the elimination of burning, the retention of branches as a mulch after felling and the reduction of competition from other species. The phased application of fertilizer was introduced in order to overcome the tendency to leaching in the sandy soils and in order to maintain the supply of nutrients at times of peak demand; this was found to be well suited to the *P.radiata* rooting habit (Boardman 1982). These practices combined with genetic selection for vigour have resulted in a general second rotation gain in yields.

It is claimed that no studies have shown that nutrient removals in logging or conversion to pine have led to productivity decline in South Australia (Turner 1983). The problem of second rotation decline in Australia is confined to soils of low nutrient status. On heavy relatively fertile clays in New South Wales *P.radiata* was thought to have improved the site index from $H_{dom(20)}$ of 60 m in the first rotation to $H_{dom(20)}$ of 70 or 80 m in the second rotation (Muir 1970).

The points of significance appear to be that:

- the problem was noticed as a result of measurements of Permanent Sample Plots, which were first established in 1935 (Boardman 1988);
- the problem occurs on difficult soils with low initial nutrient status and low water holding capacity;
- there were adequate resources to research the problem and find an answer;
- the potential for second rotation decline on infertile soils exists; the solution consists largely in good forestry practice to conserve the soil moisture content and to maintain the organic content of the soil backed up by repeated applications of fertilizer adjusted to the crop's requirements at each stage of development.

(c) Usutu plantations, Swaziland.

Monitoring of the Usutu plantations, which have primarily been established to *Pinus patula*, with some *P.elliottii* and *P.taeda*, started in the late nineteen sixties. Early in the second rotation Permanent Sample Plots were established which have been monitored ever since. Some sites are now carrying their third rotation of pine (Evans 1975,1988). In 1983 an intensive soil survey was undertaken (Morris 1986).

The findings of the soil survey are discussed in more detail in Appendix 2. Of particular note is the fact that whereas most of the area overlies granites, 15% of the plantation area is on the Usushwana complex soils overlying gabbro, and these soils are seriously deficient in phosphates. Unless corrective measures are taken yield declines are highly likely on the Usushwana soils.

The Usutu plantations lie between about 1000 m and 1450 m altitude; above about 1350 m there is a problem of litter accumulating on the forest floor on both granite soils and on soils of the Usushwana complex. The immobilisation of nutrients in the litter layer combined with their loss at harvesting might result in a deficiency of nutrients, especially nitrogen, phosphate and potassium. At one time it was the practice to burn branches, tops and also needle litter after clear felling, but this has been discontinued since 1973, because it was associated with subsequent attacks of the pathogen *Rhizina undulata*. But there is, however, evidence that when burning is not practised the accumulation of litter under second rotation crops is much greater, though the loss of nitrogen and sulphur to the atmosphere is reduced. Analysis of the growth records and the Permanent Sample Plots at Usutu has confirmed that on the Usushwana complex soils a yield decline occurs in the third rotation, of about 30%, but trials have indicated that plantations on these sites will respond to P fertilizer, which may resolve the problem .

The analysis of growth records from the plantations on soils derived from granites has proved to be more complicated. The early figures for second rotation growth indicated a faster rate in the first two years in comparison to the first rotation and then a slower rate over the next four years or so. This was explained by two facts. First, in the second rotation the trees were established onto weed free sites. Second, there had been a series of years with low rainfall at planting time in the second rotation; Usutu receives only just enough rain to support *P.patula* and therefore drought years have a critical effect on yields (Evans 1975).

Results are now available for second rotation crops at twelve years of age and for up to six years in the third rotation. In the second rotation plots there were non-significant declines of 8% on the Usushwana complex and 4% on granites. Second rotation *P.elliottii* showed a non-significant drop in height of .36 m (from 15.57 m) at age twelve. In the third rotation, although there has been the marked decline in yields on the Usushwana complex soils noted above, on one set of plots on a small area over granite there has been a significant gain of 21% over second rotation yields, while on the larger area there was a non-significant gain of 4%. The general conclusion is that on the granite soils, even after allowance is made for yield increases attributable to improved genetic materials and improved establishment techniques, no yield decline has been detected (Evans 1988).

The points of importance appear to be:

- that a system of Permanent Sample Plots has been set up so that it is possible to monitor growth with precision;

- that, whereas it has been indicated that there should be a general reduction of nutrients with time and in consequence a decline in yields (Morris 1986), it has not been possible to detect this from growth records, except on one difficult site;

- the problem of litter accumulation at higher altitudes remains unresolved and could be a cause of nutrient depletion in *P.patula* stands.

(d) Conclusion on second rotation yield decline.

There is a role for mixtures in soil management, but insofar as second rotation yield decline reflects changes in site properties, the evidence suggests that it is a potential problem on infertile soils and on some other sites, but that on these sites yield decline can be controlled by good forestry practice, in particular the matching of species to site, and the application of fertilizer to correct nutrient deficiencies. Although on fertile sites it may not yet be possible to obtain statistically significant evidence of yield decline, soil scientists have provided sufficient evidence of the likelihood of a loss of nutrients (Lundgren 1980; Morris 1986; Young 1976) that foresters cannot afford to be complacent. The need for soil conservation is evident, especially through the avoidance of compaction by heavy machinery or exposure of the soil by burning. These are not necessarily problems of growing plantations as single species or in mixtures of species.

The importance of Permanent Sample Plots as a tool to help in the detection of yield changes has been stressed in this study. But declines in yields may not be detected until well into the rotation or even into the following rotation because of problems in sampling and interpretation (Ryan 1985). Silvicultural practices which are likely to deplete the topsoil of nutrients, moisture or organic matter must be avoided on all sites.

The role of mixtures in soil management.

The situations in which mixtures might be recommended appear to be as follows.

(a) Ground cover.

The introduction of a matrix of trees or shrubs that will provide quick ground cover is often desirable on sites where it is important that soils are not left exposed for long periods, in the plantation establishment phase, due to the risks of erosion. But often the same effect can be obtained with non-woody legumes, such as lupins, or by allowing suitable herbs or shrubs to colonize the site temporarily. A situation in which it is important that the soil is not exposed is most likely to occur on rainforest sites. If protection and conservation of the soil is of critical importance, then it is probable that the site is unsuitable for clearing and consideration should be given to enrichment planting. On some sites, such as coarse sands, ground cover may be better achieved using mulches of plant residues after clearing the site or after clear-felling; the balancing of the need to protect the soil by encouraging ground cover on the one hand and to reduce competition by weeding on the other requires knowledge of the site.

Irrespective of species composition, some management regimes, which involve the destruction or removal of litter, for example as a result of the use of bulldozers to clear the site, or as a consequence of burning slash or through collection of litter for livestock bedding or as fuel, are likely to cause a marked reduction of organic matter in the topsoil. This has an adverse effect on cation exchange capacity, water availability and soil structure with a consequent risk of erosion. Teak plantations in India, Indonesia and Trinidad or eucalypt plantations on steep slopes in Ethiopia are some examples. These problems are primarily of administration and protection than species selection or composition.

(b) Promotion of litter breakdown.

On sites where there is a risk of a litter build up there is a case for introducing an admixture of tree species whose leaves are known to be favoured by soil biological agents and which will therefore promote quicker litter breakdown and nutrient mineralization. *Cordia alliodora* leaves decomposed more quickly when the trees were grown in mixture with other tree species than as a pure crop (Babbar and Ewel 1989). The same effect can also be achieved by alternating rotations of species tending towards litter accumulation (e.g. conifers on some sites) with those that promote its decomposition (e.g. some broadleaf species). Sometimes a reduction in stocking will promote the natural regeneration of a beneficial understorey of small trees, shrubs and herbs, which will achieve the same objective.

Nitrogen fixing.

The introduction of nitrogen fixing species can benefit overall yield on nitrogen deficient sites. Increases in soil nitrogen have been noted in Hawaii (DeBell et al. 1985), India (Samraj et al 1977), but whether nitrogen fixers grown in semi-shade as an understorey species actually fix much nitrogen is uncertain.

Conclusions on soils.

1. Many of the soils available for forestry plantations in the tropics and sub-tropics are inherently infertile and are easily degraded.

2. Some of the methods used for clearing sites for planting are excessively destructive of the soils. These include the use of heavy machinery and indiscriminate use of fire which result in the removal and exposure of the top soil. Soils under rainforests will be damaged if these techniques are used. It should be noted, however, that many of the forest plantations in the rainforest zone are being established on sites that have already been degraded, and in fact afforestation in the tropics is more usual in grassland, scrub, savanna woodland or disturbed vegetation than in dense polyspecific forests (Wood & Dawkins 1971).

3. The maintenance of the topsoil organic content and the rapid recycling of nutrients by the decomposition of the litter layer on the forest floor are important contributors to the maintenance of soil fertility.

4. Losses of nutrients from exploited plantations are inevitable (through removal of biomass at harvesting), but second rotation yield decline should only be expected on nutrient deficient sites and can be corrected. Second rotation decline is not an inevitable consequence of monospecific plantations. Many of the fertility problems associated with monospecific plantation forestry can be overcome, or at least greatly ameliorated, by good forestry practice, such as care in the use of clearing techniques, particularly in the use of heavy machinery and fire, the maintenance of a balance between soil exposure and control of competition from other species, the avoidance of over-stocking (so that small tree, shrub and herb strata can develop) and the addition of supplementary fertilizers. These practices are equally appropriate whether the plantations are mixed or pure.

5. Mixed plantations can make a contribution to the management of soil fertility in some circumstances:

- to provide heterogeneity of leaf litter to help in promoting litter decomposition and thereby to prevent the accumulation of litter on the forest floor and so to maintain the organic matter content of topsoils;
- to provide ground cover in order to reduce the risk of erosion by wind or rain and also prevent insolation of the topsoil and the consequent damage to soil microfauna and microflora; this is of particular importance in the establishment phase.

These two effects can often be achieved by encouraging and controlling the growth of natural vegetation under pure plantations:

- the admixture of nitrogen-fixing trees and shrubs, although these are likely to be beneficial on sites on which only nitrogen is deficient, while other nutrients and moisture are not limiting and as previously stated, these species may not be effective growing as understorey species. The number of suitable sites is likely to be limited;
- other potential advantages to soil management of mixing species, such as the "nutrient pump effect", in which deep rooting species tap nutrients in the subsoil and deposit them at the surface in their litter, and beneficial interactions with mycorrhizae, are unproven in the tropics.

3.2 CLIMATE AND POLLUTION.

Climate change

The changes in the climate that are predicted in the short- to medium-term may have beneficial or harmful effects on the growth of trees and forests. The increase in CO_2 levels and the rise in temperatures may increase growth rates, but decreased insolation and drought may reduce them. Some climates may become more variable. The present ranges of species or provenances that are not sufficiently buffered against environmental changes, such as climate change, will be reduced and some species or provenances may become extinct. This section discusses the likely reaction of single or multi-species plantations to climatic change.

It is known that the concentrations of certain gases, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (NO_2) have increased since the start of the Industrial Revolution in the mid-18th century and it has been predicted that this will lead to global warming (the greenhouse effect). One estimate is that since 1765 levels of CO_2 have increased by 25%, of CH_4 by 100% and of N_2O by 10% (Jones & Wigley 1990); another estimate is of 26%, 143% and 17% respectively since 1850 (Andrasko 1990). CO_2 concentrations have varied throughout geological time, but present day levels are as high as they have ever been in the last 160,000 years (Andrasko 1990). Estimates of annual increments of CO_2 are imprecise; one source alone gives a range from .25% to .7% (Andrasko 1990), implying that a doubling of CO_2 from pre-Industrial Revolution levels could occur as early as the middle of the 21st century or as late as the 23rd century.

There is a general concensus that global temperatures have risen by 0.5°C over the last century (Andrasko 1990, Jones and Wigley 1990). The increase in temperature, however, cannot be directly related to the increase in CO_2. There are other factors which cause a rise in temperature such as volcanic eruptions, solar flares and the movement of ocean currents, which tend to occur erratically. The effect of CO_2 could account for a rise in temperature over the last century as high as 0.8°C or as little as 0.2°C (Jones and Wigley 1990).

If the concentration of atmospheric CO_2 doubles, then global temperatures may increase by 3°C to 5°C and regional averages could vary by -3°C to +10°C; global precipitation might increase by 7% to 15% and regional averages vary by -20% to +20%; regional soil moisture may vary by -30% to +30% (Andrasko 1990). Some calculations have been made for South East Asia and West Africa which predict that for a doubling of atmospheric CO_2 there will be a general increase in temperature of 3°C in South East Asia and of 4.5°C in West Africa; rainfall changes include significantly increased seasonal variation - more rain in the monsoons and less in the inter monsoon dry seasons - for South East Asia and a slight gain (0.1 mm/day) in West Africa.

The effect of temperature and rainfall changes on vegetation is even more difficult to predict than the changes themselves. While temperate and sub-tropical forests may spread towards the poles, the sub-tropical moist forests may be replaced by tropical dry forests and grassland, savanna woodland and deserts may expand (Andrasko 1990, Calabri 1991). There may be an increase in the frequency and severity of forest fires and pest outbreaks as a result of the accumulation of litter and dead wood arising from increased vegetative growth due to CO_2 enrichment.

It is possible that one of the effects of warming will be a general extension of dry zones away from the equator. But the warming and drying effect will not be uniform over the whole world; in some localities temperatures may drop or rainfall increase and in many areas rainfall will become more erratic. At the extremes of the Intertropical Convergence Zone in Africa rainfall is already erratic and it can be expected to become more so.

The first effect on tree crops is likely to be that more frequent failures of the rains at planting time will make regeneration more difficult. If such an effect occurs then more drought resistant species will need to be selected for planting. Those species considered to be at the limit of their range will have to be replaced by more drought hardy species or be proven to be capable of maintaining their growth. Drought induced mortality of mature trees may take longer to become apparent; but these trees will be under stress and therefore the incidence of pests and diseases can be expected to increase and the fire hazard can become worse. Climatic change can also be expected to cause pests and diseases to change their range. The fungus *Guignardia aesculi* on horse-chestnut (*Aesculus hippocastaneum*) has, in recent years, moved north of the Alps and is now to be found even in southern Scandinavia; *Ceratocystis fimbriata*, a disease of plane trees (*Platanus* spp), and its insect vector are moving north from the Mediterranean. Although no connection with warming of the climate has been proved, these examples give an indication of trends which may develop (Donnabauer 1991).

A policy of mixed planting will be justified on sites where present rainfall is adequate but variable and it is hoped to establish a medium to long rotation valuable species that is lacking in drought hardiness. In such instances a mixture of less valuable, but more drought hardy species will act as an insurance against total biological failure. There is no evidence that mixtures will enhance the survival of less hardy species.

Bruenig (1991) considers that climate change is happening and points out that "...this change will affect the functions of forests and consequently their role in the biosphere and their utility to humanity." He points to the need for foresters to structure man-made forests to be more resilient to climatic changes and extremes, to maintain high levels of biodiversity and to choose species and design species mixtures that will adapt not only to future changes in climate but also to changes in the economic and social environment.

Techniques are now available for selecting and breeding trees adapted to specific sites and conditions. There is therefore potential to establish plantations relatively resilient to a changed climate, but for this to have a positive effect the changes should be predicted accurately. The less variation there is the greater the risk and the largest risk will be in monoclonal plantations. Mixed plantations could be part of the strategy. However, provenances and clones that are highly specific to a site are acceptable in short rotation projects, providing there is a pool of genetic material adapted to different climatic conditions which can be used to replace unsuitable genetic materials at short notice. "Insurance" can be taken out in the form of more intensive research into genetic variation or in the mixture of species in a plantation. This is discussed further in chapter 7. The choice depends very much on the objectives of management and financial resources.

CO_2 reservoirs

Growing trees remove CO_2 from the atmosphere and store it in the form of cellulose. When the plantings are used (for instance for firewood) or when they reach maturity, however, the death of individuals and the natural processes of decay return CO_2 to the atmosphere at the same rate as it is removed so that there is no net increase in storage. The use of plantations to sequester CO_2 will be most effective when they are used as a short-term solution or when the final product is timber which is converted into durable products. This immobilizes CO_2 as cellulose for long periods after harvesting. Fuelwood plantations make a contribution while the trees are growing and could help reduce the rate of increase of atmospheric CO_2, especially if the fuelwood is subsequently used efficiently. Fast growing, light demanding species would give an early effect, but if an admixture of shade bearing tree, shrub or herb species can improve the total yield of a site then a mixture will be a more effective CO_2 reservoir.

Microclimate.

Forests ameliorate the local climate, lowering temperatures and increasing humidity. Mixed plantations which produce multilayered forests are more effective in achieving this. The contrast between the more uniform, microclimates to be found in the mixed (and all aged) mahogany/teak/jak plantations and the relatively more extreme climatic fluctuations to be found in the pure teak plantations at Sundapola, Sri Lanka is marked (Ng 1991).

A windbreak moderates the microclimate for up to twenty or more times its height to leeward. A windbreak is most effective if, rather than acting as a wall which causes turbulence downwind, it filters the wind and has a profile that allows the wind to pass smoothly over the windbreak. A windbreak having tall trees at the centre and shorter ones at the outside will reproduce this profile. This can be achieved by using a mixture of tall and short species.

Pollution

Forest damage caused by air pollution arising from anthropogenic sources (such as sulphur dioxide, acid rain or heavy metals) is primarily a problem in countries where there are heavy industries, electric power generating plants and large numbers of motor vehicles, all burning fossil fuels. While these problems are acute in developed countries, however, some tropical countries, such as India and Brazil, have heavy industries and there is potential for damage, although no records of this have been noted. It is likely that in developing countries strong economic pressures combined with weak social and political pressures on industries will cause pollution to continue and even get worse. Some species are better adapted to withstanding pollution than others; for example in the Carpathian foothills of the USSR, an oak/silver fir mixture was found to be more resistant to kainite dust, hydrochloric acid and organic fats from a potash factory than either species alone or any other species. A young oak/alder plantation withstood soot and carbon monoxide from an activated carbon factory better than other species (Voron 1979). In the hills around Mexico City, one of the most heavily polluted cities in the world, natural forests of pure *Abies religiosa* have been almost completely killed as a result of high levels of ozone pollution, while other species have survived (Ciesla and Macias 1987, Whitmore 1991) including *Pinus hartwegii* growing at higher elevations. In the San Bernardino Mountains of California *Pinus jeffreyi* and *P. ponderosa* have been adversely affected by air pollution, while *Calocedrus decurrens* (incense cedar) and *Abies concolor* (white fir) have been relatively unaffected (Miller and Elderman 1977). These references illustrate that individual species may be tolerant of various forms of pollution but there is no evidence that the examples of mixtures of species proving more resistant to pollution were in fact more successful than the same species grown in pure association. Presumably a mixture of species resistant to different types of pollution would be an "insurance" against complete failure in a situation where the level or the type of pollution were expected to change with time.

The use of municipal waste waters to irrigate plantations on sewage farms is becoming more common in the tropics. In South Australia a mixture of *Casuarina glauca* and *Eucalyptus occidentalis* has been found to be effective in using saline effluent; in less saline conditions *C.cunninghamiana* can be used in the mixture. *E.camaldulensis* and *E.occidentalis* mixtures are also likely to tolerate conditions of flooding and salinity. A two tier plantation disposal system is being developed in which a vigorous potentially high value species is established and irrigation from municipal reclaimed water is matched to saturation deficiency; other species are grown on a site simulating a winter-spring flood plain system during the rainy season. It is intended to use mixtures of two or three species (Boardman 1990). These examples offer, however, no comparison with the performance of a single species not grown in mixture.

3.3 FIRE

Global statistics on forest fire incidence and area burned are lacking, but, between 1980 and 1988, Europe (excluding the USSR) and North America suffered an average of about 20 000 forest fires yearly, most of which arose from human causes such as negligence and arson. The area burned each year was about 4 million ha, causing enormous but unquantified losses of timber, environmental benefits, amenity, cultural values and even property and human lives (Calabri 1991). How many of those fires occurred in plantations is not recorded but in Brazil over 200 000 ha of plantations were burned between 1983 and 1988, out of a total plantation area of 6 million ha. This may appear a very small proportion of the total area but the monetary cost to the nation was estimated to be $US 199.6 million (Soares 1991).

The reduction of fire hazard may be achieved through various interventions, for example, mechanical means such as firebreaks or roads (which are costly and may lead to loss of amenity), the use of herbicides (which is both costly and environmentally damaging) and biological means, such as grazing within woodlands, which is difficult to control and to reconcile with forest and soil conservation. Prescribed burning has been proposed but carries the risk that the fire may spread and in Europe and North America its use may not be acceptable to the public in some places (Calabri 1991).

The incidence of fires in forests (including plantations), is growing rapidly around the world, but there are difficulties of combatting or preventing forest fires in ways that are environmentally and socially acceptable. It is therefore surprising that the effect of mixed species plantations on severity of fire damage has not been more widely tested. Velez (1991) has drawn attention to the need for discontinuities in plantations and the modification of inflammability models (which are related to the moisture content of the fuel and the structure of the vegetation) to slow the spread of fire. The incorporation of other species, especially hardwoods, in intimate or discrete mixtures would meet these aims.

3.4 CONSERVATION OF ANIMAL AND PLANT GENETIC RESOURCES

General considerations

Plantations are specialised but generally simplified ecosystems, in which plant diversity has been reduced in order to allow the maximum production of a single valuable component. The most valuable component is usually the woody stem of the planted tree species. When indigenous plant communities (forest, woodland or grassland) are converted to monospecific or polyspecific plantations of native or exotic species, with the main purpose of wood production, generally there will be a reduction in both habitat and species diversity at that site. This may affect wildlife requirements for food or shelter, or both.

The biological diversity at a site is associated firstly with the diversity of habitats or communities at that site in terms of structural variation (forest, grassland habitats, etc.); and secondly the diversity of species within each habitat or community. Habitat diversity varies at several levels - from individual trees to block sizes of several hectares (e.g. Clout 1985, Gepp 1985, discussing bird diversities in plantations in New Zealand and

Australia respectively). A growing literature in "conservation biology" addresses the issue of diversity (e.g. Wilson 1988, Soule 1986).

Diversity in the plantation tree layer can thus arise in several ways:

- from multi-species plantings;
- from mixed age plantings in mixtures or in adjacent small blocks;
- from retaining some level of natural vegetation as patches or as individual trees or shrubs within the plantation.

The maximization of cost effective timber yield per unit area is likely to be incompatible with maintaining either high levels of "natural" biodiversity or high densities of favoured wildlife species. But this does not mean that plantation forestry is necessarily always detrimental to wildlife interests. Plantations have a major role to play in wildlife conservation and management at both the national and local level. This role may be direct - in providing a habitat for target species; or indirect - in relieving pressure on other wildlife habitats.

Any form of forest management, including the planting of trees, is going to change not only the pattern of biodiversity, but also wildlife parameters such as biomass and species densities. Whilst the replacement of a degraded scrubland by a productive multispecies plantation may greatly increase wildlife species richness and biomass, this may be seen as a negative change if the original scrubland fauna and flora is globally at risk.

Rehmani (1989) describes the loss of the natural dry grassland communities of central India with the endangerment of the associated fauna of bustard, gazelle and wolf. Its replacement with eucalypt plantation which may have higher densities of *Axis* deer is not a conservation gain if the aim is to conserve the maximum number of wildlife species.

This change in natural biodiversity has two implications in terms of designing and managing plantations for the conservation and management of natural resources. These are:

- the conservation of overall biodiversity - the total range of genetic, species and community diversity of all plants and animals at that site;

- the management of the plantation habitat to produce wildlife species of potential positive benefit (i.e. deer for hunting) or to reduce species of potential negative benefit (e.g. pest species which decrease wood production).

These two objectives and ensuing management activities are so different as to warrant separate discussion.

Conservation of biodiversity

Background

The necessity for slowing the rate of loss of total biological diversity, especially that contained in tropical forest ecosystems, is well described in recent literature and plantation forestry has a significant role to play in conservation planning and management (Poore & Sayer 1987 for example). Three activities are of importance:

- Developing forest cover, through afforestation or reforestation, to increase the effective size of the forest or protected area. This could be in general, to raise populations of key wildlife species above minimum levels for viability by creating a larger area, or, more specifically, by providing cover along dispersal routes or "corridors" used by these species.

- Developing peripheral plantations to act as a buffer zone for resource use around forested areas that are threatened by intense exploitation pressure without due management.

- Developing multiple-use resource plantations for rural communities so as to reduce their need to exploit nearby protected areas of conservation importance. These plantations need not be adjacent to the protected area.

The first category of plantation and to a lesser extent the second would better fulfil their conservation function if their structure and composition resembled the natural forest community. Multi-species plantations which allow an understorey and have a structural diversity through multi-age block planting and the maintenance of gaps, etc are thus of greater importance than structurally homogenous monospecific blocks. There is an extensive literature on the design of man-made (and managed) forests for joint conservation/ production objectives from the United States (e.g. Thomas 1979, Harris 1984, Hoover & Wills 1987, McTaggart-Cowan 1985, Salwasser 1985, 1990) and elsewhere (Ratcliffe & Petty 1988; Hobbs, Saunders & Hussey 1990; and generally, Poore & Sayer 1987; Kemp, 1992).

For conservation purposes, species mixtures have to provide real ecological differences; two different conifers would not necessarily provide benefit over a single species. Mixtures of a deciduous and evergreen species or the addition of edible fruit or fodder species to a principal timber species can provide real differences in niche availability and hence habitat diversity. In Indian plantation forestry practice species mixtures are now being considered, where some 10 - 20% of trees are included because of their value to local people or wildlife (Wildlife Institute of India - forest management guidelines). Note that modern conservation sees a strong linkage between satisfying resource requirements of people and ensuring sustainable conservation.

Species mixtures can include mixing the main plantation species with species already *in situ*. This can be in blocks or strips of natural growth or by the retention of individual tree species e.g. figs or over-mature "snag" trees which provide nesting sites or insects as food (Rodgers 1992). Natural openings such as rocky areas, marshy areas should be retained.

Plantation management as well as the initial design is of importance. Plantation thinning and felling practice can be designed to benefit diversity of plant and animal species. Some old growth can be retained and some fallen logs left *in situ* for example. Specific management practices will follow from the objectives of the plantation as a whole and the objectives of each particular zone in the plantation. Multi-purpose plantations are best considered through internal zonation, where different priorities can be given to different objectives within each zone.

Where plantations are to be developed adjacent to natural forest of biological importance, it is essential to ensure that plantation mixtures do not include invasive species. The development of commercial hardwood plantations in the East Usambara Mountains of Tanzania used the locally exotic *Maesopsis eminii* as a nurse crop for the valuable endemic *Cephalosphaera usambarensis*. The former is now considered a major pest species, aggressively invading natural forest in competition with local species (Hamilton & Bensted-Smith 1990).

Measures to increase species diversity in plantations

It is possible to give some general guidelines for increasing total diversity in plantations, assuming that plantation objectives indicate the need to consider the conservation of the fullest range possible of native plant and animal species. The guidelines are as follows:

- maintenance of areas of natural habitat within or close to the plantation area; there is some doubt whether these patches should be large or whether groups of smaller areas are to be preferred (Clout 1985); this will depend on the exact objectives, such as, for example conservation of intraspecific variation of plants, when patches would be appropriate, or the conservation of large mammals, when large areas are required. In Queensland 500 ha of native forest types are usually retained for every 4000 ha of plantations established; at least 200 ha of the reserved forest is in a single block. These areas are additional to those excluded as not suitable for planting, because of steepness, rockiness, salinity, etc. (Francis and Shea 1987);

- retention of indigenous forest strips, especially along water courses, linking larger natural reserves for which they form corridors for movement of wildlife;

- a planting plan that, as far as possible, juxtaposes compartments of different species and of different ages;

- the retention of indigenous trees or shrubs within the plantations, which may be justifiable for the encouragement of specific wildlife species e.g. the retention of flowering trees to attract nectar feeding or insectivorous birds, fruit trees for bats or leaf fodder for primates, etc.;

- care in planning the felling operations to allow escape cover and reduce the period of disturbance to a minimum.

Wildlife management

Wildlife for utilisation

For many plantation areas there will not be an overriding requirement to maintain or support the natural level of total diversity of plants and animals. Plantation design could then maximize e.g. timber production. However other plantation products could be of subsidiary importance, for example species of secondary commercial value such as bamboo or rattan, or of subsistence values such as fruit or leaf fodder. Wild animal products fit within both categories. For example at a commercial level, sport hunting of tigers and other species, and the cropping of populations such as muskdeer, butterflies etc. At subsistence level, the managed hunting of meat animals and other food species can be of great value to rural people and often create support for plantation inputs at local level.

This section describes factors affecting the design and management of a plantation for increasing such wildlife products. The planning stage is of great importance and should involve identification of products seen as important by local communities. Large plantation blocks would probably involve several zones giving different levels of priority to different objectives and products.

Plantations as wildlife habitat

Plantations may provide ideal habitat conditions for certain generalist species at some particular stage of the plantation cycle. This could be at the more grassy post-clearing and seedling stages for grazers, or at the older more mature crop stage, especially if there is an understorey vegetation layer for forest dwelling browsers. This means that the pattern of wildlife use resulting from the establishment of plantations is not simply to cause an exodus of wildlife from the area, as some generalist species will remain, and plantations may attract or support different species from those that existed in the previous state. The pattern of species use will change through the life of the plantation. Introduction of desired species may be necessary or beneficial at different stages.

Large blocks of pole stage exotic pine plantations were found to be particularly poor in wildlife in New Zealand - for example bird species (Clout 1985) - but taking all plantation age classes into consideration, it was found that the number of species in the plantation was almost the same as in the native vegetation in South Australia (Gepp 1976). Higher densities of insectivores, macropods and some seed-eaters may occur in plantations than in natural communities (Gepp, 1985). In Knysna, South Africa, although the total requirements of bushbuck *(Tragelaphus scriptus)* were best met by the indigenous broadleaved evergreen forest, the clearfelled areas were used at night, and dense *Pinus radiata* and *P. elliottii* plantations by day (Odendaal and Bigalke 1979). *P. radiata* plantations on the Kikuyu Escarpment in Kenya were less favourable to bird species with specialised habitat requirements, but several generalist species with broader habitat requirements adapted well to them, and palaearctic migrants made greater use of plantations than natural forest (Carlson 1986).

The creation of a mixed stand may even be deleterious for some wildlife species. In Britain the admixture of oak into a pine community is known to be fatal for red squirrels, because grey squirrels are far more successful in the conifer/broadleaved mixture and the indigenous red cannot coexist with the exotic grey squirrel (Kenward 1990).

The boundary between two habitats, whether between forest and agricultural areas or between two structural forest or plantation types, often has a higher number of species and biomass than any one of the communities (Moss 1979; Friend 1980). This is the well known "edge effect" of wildlife biology. Greater levels of "edge" can increase numbers of several generalist herbivores, deer being the prime example. Edges are not beneficial, however, when the conservation goal is to foster a habitat specialist which is dependent on large areas of forest. There is increasing debate on the values of edges in conservation biology (Reese and Ratti 1988).

Large mammal use of plantations is much greater when there is an understorey of native plants which provides shelter and food (Gepp 1985). If such wildlife production is a required output, then the plantation canopy should not be allowed to become too dense. In South India in a teak plantation within a wildlife area the thinning operations were combined with tending and weeding activities which resulted in a homogenous grass layer. This attracted the generalist *Axis* deer. But densities of elephant, sambar deer *(Cervus unicolor)* and sloth bear declined as they are all dependent on a denser forest and shrub cover. Management was advised to consider leaving two out of every ten rows untended (Rodgers 1992).

In Swaziland the establishment of well protected exotic pine plantations on highveld grassland which had been used for sheep farming and had been regularly hunted, has resulted in an increase in some wildlife species. Bushbuck and leopard and many other species of mammals are now common (Evans 1988). In this example the increase in wildlife has in part been due to the protection that could be afforded in the plantations, but which was impractical on the open grassland, but it also reflects an increase in species resulting from the creation of new habitats and to the favourable conditions created at the boundaries of plantations and grasslands or rides. Generalist wildlife species are at far higher densities in the plantation areas of Bori Reserved Forest in central India than in the adjacent neighbouring natural moist deciduous teak community. The plantation area is a mixture of pure teak, failed teak turned into bamboo plantation, grassy clearings and patches of natural forest. This is now the preferred tourist area with high probabilities of sighting tigers and several large herbivores (Rodgers 1992). Thirty year old mixed plantations of indigenous *Dalbergia sissoo*, acacias, and *Bombax* sp. on the grassland areas of Dudhwa National Park in North India are a major food and shelter resource for large mammals and contribute to overall wildlife value. This contrasts with nearby stands of non-palatable teak and eucalypt which are little used by wildlife species (Rodgers 1992).

This pattern of increased wildlife abundance may have its disadvantages since some forms of life, whether insects or mammals such as elephant, deer, pig or monkey, can cause considerable damage in plantations. Such damage can sometimes be reduced by planting unpalatable species at the boundaries between plantations and indigenous forests. In Sabah it was noted that deer damage to *Gmelina arborea* plantations declined to negligible proportions 1 km from the indigenous forest (Duff et al. 1984). It is possible that a "barrier" of unpalatable species, such as *Acacia mangium*, established next to the boundary with the natural forest will reduce damage by browsing mammals. Morphologically different species, such as are contained in the understorey of a forest plantation, can also be a natural barrier. On the other hand some insectivorous birds are beneficial in helping to control insect attacks in plantations and can be encouraged by retaining strips and mosaics of natural forest (Aracruz 1988). Natural forest strips will also harbour greater arthropod diversities which will be advantageous in dealing with pests (through parasitic and predatory *Hymenoptera* for example). Action that can be taken before plantation establishment and during plantation management to increase the biomass of desired species of wildlife includes:

- the retention of strips of natural cover especially along streams and drainage lines;

- a planting plan that, as far as possible, juxtaposes compartments of different species and of different ages, and of grassy clearings and other natural vegetation;

- extreme care in the use of fire which can have positive and negative impacts. Many grazers benefit from an occasional burn. Forest specialists will not;

- a policy of heavy thinning in the middle and late stages of plantation development, which will encourage the indigenous understorey and ground cover in the plantations;

- the retention of indigenous trees and shrubs within the plantations, which may be justifiable for the encouragement of specific wildlife species e.g. the retention of flowering trees to attract nectar feeding or insectivorous birds, fruit trees for bats or leaves for orang-utans.

Conclusions on the conservation of animal and plant genetic resources

Any natural change or man-induced intervention in an ecosystem will affect the wildlife population; the simplification and specialisation of the tree layer in the ecosystem will result in a reduction in wildlife diversity in comparison to a natural community, but the impoverishment will not be uniform. To stigmatise monospecific plantations as "biological deserts" (quotation noted in Friend 1980) is more an expression of emotional commitment than a rational analysis of the problem. Plantation management can go a long way to improving both natural diversity levels and to increasing wildlife amenity values.

Good planning, starting with a statement of what priority and specific aims the conservation of biodiversity or the production of wildlife should have, is essential. Various strategies are available, including the broad sense mixing of species in neighbouring compartments, which will encourage wildlife in industrial plantations without the creation of mixtures in the narrow sense of polyspecific compartments. Where mixed plantations are appropriate, whether for specific products or for rehabilitation, diversity of structure and age is as important as diversity of species to encourage wildlife.

3.5 INSECTS AND DISEASES

There are few references in the forestry literature which compare the effects of mixtures in artificial stands on the incidence of insects and diseases or of the effects of insects or diseases on mixed stands. This makes a comparison of pure and mixed stands difficult. Extrapolation of information from agrosystems is not always sound because of the longer time scales involved in forestry, although the tendency towards short rotation tree crops, for example *Albizia falcataria* with a rotation of five to eight years in Malaysia or *Eucalyptus* species with a rotation as short as five years in Brazil, makes the comparison more valid. The tendency has been to compare pure artificial stands with mixed natural stands and in consequence other site and environmental factors have confounded the comparisons.

Stability of forest ecosystems

One of the primary factors which regulate pest populations is the availability of suitable host material. Natural forests which contain a mixture of species achieve a state of complexity in which the vegetation is broadly in balance with pests and diseases. These ecosystems include a wide range of insects, fungi and bacteria living on the trees and herbaceous vegetation. An increase in the proportion of any host plant in an ecosystem tends to be followed by a corresponding increase in the pest or pathogen population whose activities eventually reduce the host population back to a low level. Insects and diseases help to control the size of individual species populations and thereby maintain the species diversity in that ecosystem; subsequently the populations of these organisms are themselves controlled by the reduction in available food and by the activities of natural enemies. Way (1977) has described the spruce budworm *Choristoneura lumiferana* in eastern North America as an example of this species-destabilizing, but community-stabilizing activity. The tendency is, then, for the insects and diseases to prevent any one plant component of the ecosystem dominating it. Therefore the simplification of an ecosystem to one tree species, as in a monospecific plantation, would appear to increase the risk of a serious attack by an insect or disease unless other habitat requirements of the attacking organism can also be managed (Way 1977).

Diversity is greatest at the interface between two types of habitat. This can lead to problems with pest species which require elements of each habitat for their survival. The problems of raising sorghum in Sudan are an example of this; many of the pests, such as Quelea finch, grasshoppers etc. live in the natural bush. In Bangladesh the invasion of *Gmelina arborea* plantations by the mistletoe *Loranthus parasitica*, which invades from neighbouring natural forest, is another example on a smaller scale (Gibson and Jones 1977). One solution to this problem is to continue the simplification process ruthlessly so that there is only one crop over a wide area (Way 1977). The agricultural practice of large scale monocropping, such as wheat farming in the prairies, has the incidental effect of eliminating interface zones, but this is a solution that, even if it was appropriate, should not be applied in the marginal and highly variable sites usually made available for large scale forestry, where the first priority is to match species to site. There are numerous examples in both agriculture and forestry where interfaces between two ecosystems provide habitat requirements for natural enemies of pest species.

It might be thought that natural communities, especially where they are diverse, though capable of harbouring pest species, should be less susceptible than monospecific crops to catastrophic attacks. But diversity in itself does not prevent catastrophes especially in the case of introduced pests. Some of the catastrophic losses caused by introduced diseases in both Europe and North America - Dutch Elm disease, *Ophiostroma (=Ceratocystis) ulmi*, Chestnut Blight, *Endothia parasitica* and White Pine Blister Rust, *Cronartium ribicola* - have occurred in natural polyspecific communities. The balance achieved over many years in natural forests is disrupted when new pests are introduced which have not co-evolved with their new host, are introduced into ecosystems which lack natural enemies or when new tree species are established in an ecosystem. In the last case the relative advantage of an exotic crop is frequently attributable to a lack of pests in its new surroundings. This advantage will diminish as local pests and diseases adapt to the new host and will be eliminated if an exotic pest or disease is introduced (Gibson and Jones 1977).

Large areas of pure plantations have been established and though there have been epidemics and failures, the majority of the plantations are reasonably successful. An outstanding example is that of rubber (*Hevea brasiliensis*) which has been grown as an exotic in pure stands in Malaysia for over a century with remarkably few problems from pests and diseases (Ng 1991). Outbreaks of pests and diseases in plantations, whether pure or mixed, are frequently a secondary problem due to failure to match species to site, poor management or other forms of stress.

The mechanisms and stratagems by which insects find a host tree and the mechanisms by which the enemies of those insects find their hosts are varied and complex. Increased species diversity in plantations can be of assistance in preventing attacks on trees by providing camouflage for the crop at risk, by creating barriers or by providing food and refuge for the natural enemies of foraging insects. In Poland the use of the *places complexes* system has been developed (Birot 1991), in which monospecific stands of *Pinus sylvestris* are broken up with small blocks of a few hectares of highly poly-specific plantation in order to diversify the wildlife habitat and to encourage the presence of birds in particular, with the aim of controlling pest-insect populations (an example of the beneficial effects of interface zones discussed in the section on Conservation). The possibility that a mixture of species may provide alternate hosts may be harmful if the alternate host is essential to the life cycle of the pest, or beneficial if the alternate host distracts the pest from a more valuable species. On the other hand decreased diversity can dislocate the pest's life cycle in several ways, such as by depriving it of alternate food sources if they are needed, by reducing the diversity of contiguous habitats in which many pests thrive, or by diluting the effect of the pest by the volume of the material produced. Many pest species have a high reproductive potential, however, and are able to expand their numbers in response to a high proportion of suitable host material. Decreased diversity can also aid enemies of pests by decreasing the occurrence of their enemies. Little, however, is known about the nature of spatial diversity that hampers pests (Way 1977).

Some opposing views.

There are sharply divided views on the desirability of pure plantations with regard to the abundance of pests. Boyce (1954) expressed many of the views of the proponents of mixed forests. He advocated indigenous species rather than exotic, natural regeneration rather than planting and mixed rather than pure plantations. He claimed that a pure stand is ideal for a pathogen to build up to epidemic proportions and cited the failure of rubber plantations in South America as a result of severe infestation of South American Leaf Blight (SALB). Rubber occurs naturally as a scattered tree in South American forests where the pathogen is also present. It does little harm to the wild rubber tree, but pure plantations were attacked and failed and so it has been argued that pure plantations, which provided a large volume of host material, were a causal factor leading to the failure. It has been noted, however, that the plantations in question were in fact established using seedlings reintroduced from Malaysia. SALB does not occur yet in Malaysia and furthermore all rubber trees there originate from an initial introduction of 22 seedlings (Chou 1981). It is not surprising that planting material having such a narrow genetic base and which had been bred in the absence of any selective pressure for resistance to SALB should fail.

Perry and Maghembe (1989) in their appraisal of plantation forestry and ecosystem concepts noted that diversity is an important defence mechanism against pests and diseases. The statement that "the chances that a genetic monoculture will be robust against pests and diseases over the time period required to reach maturity seems small... the evolutionary capacity of short-lived pests and pathogens is enormous", correctly draws attention to the risks of epidemics in monoclonal plantations and to the fact that pests often pass through several generations of breeding and natural selection in a year (as compared to several years or even decades in most tree species), and that they therefore relatively easily can overcome various types of disease resistance originally found in the host species. Risks can be minimized through short rotations (taking calculated risks), rotation of clones in space and time, and alternative end use options in the case of disease, based on early harvesting and replacement of diseased clones. Large-scale clonal plantations, such as those in Congo (see e.g Delwaulle 1989) and Brazil (Burley and Ikemori 1988; Campinhos and Ikemori 1986), have been established with these considerations in mind and, although not without problems, generally have avoided large-scale pest attack. Thus, provided that a broad genetic base is maintained in separate base populations, to be used as "back-ups" for narrowly-based plantations or plantations established using single clone blocks; and provided adequate attention is given to the continuing development of new high-yielding clones for intensive tree farming activities, the use even of monoclonal plantations can be biologically as well as economically feasible.

Perry and Maghembe (1988) also cite the failure of *Pinus radiata* in Africa after the introduction of *Dothistroma* blight, attacks by the native cerambycid borer *Oemida gahani* on *Cupressus lusitanica* in East Africa and the fact that several pines in Southern Africa suffer severely from *Diplodia pinea* as arguments against the planting of pure stands. But it is by no means certain that pure stands are the prime cause of these problems. Isolated *P.radiata* are just as susceptible to *Dothistroma* blight as pure plantations (Gibson and Jones 1977). *Dothistroma* blight is of little significance in the south of Australia. On the other hand it has been devastating in Africa where *P.radiata* has been planted off-site in summer rainfall zones. *Oemida gahani* gains entry through wounds such as pruning scars, but has been largely controlled by better forest hygiene to remove breeding sites in slash and debris (Gibson and Jones 1977). *Diplodia pinea* is as serious a disease on isolated trees as in plantations and is prevalent where pines are planted off-site in Southern Africa (Barnes and Mullin 1976).

There are other examples of pest and diseases that cause severe damage in plantations, but the prime cause cannot be attributed to the fact that the plantations are monospecific. The root decay fungus *Heterobasidion (=Fomes) annosus* is a wood destroying basidiomycete that colonizes woody residues, such as stumps left in the ground in a clearing operation or as a consequence of thinning operations. It can occur in either pure or mixed plantations but since it is transmitted by root grafts, pure plantations favour the spread of the disease. *H. annosus* is, however, also thought to be favoured by sites from which other antagonistic fungi have been eliminated; this occurs when plantations are established on abandoned farmland (Gibson and Jones 1977). For this reason the disease may be regarded as a consequence of failing to match species to site as well as a disease of monospecific crops.

Rhizina undulata infection of pines is associated with the use of fire and so is another example of a disease owing more to the prehistory of the site than to the fact that the crop is monospecific. Because *R.undulata* causes so many problems, the practice of burning plantation residues after clear felling has largely been abandoned for sites planted to pine in southern Africa as well as in northern Europe.

In Ghana the scolytid beetles *Xyleborus mascarensis, X. sharpae* and *X. semiopacus* caused extensive damage and death in line planted *Khaya ivorensis* and *Aucoumea klaineana*. The problem was attributed to the creation of a large amount of woody debris as a result of refining operations to open up the forest for line planting. This debris formed an ideal breeding ground for the insects and when it became depleted they turned to the transplants (Gibson and Jones 1977).

Pineus pini is an introduced aphid in Africa and is an example of an insect that has found natural polyspecific stands and monospecific plantations equally attractive. *P.pini* has been observed attacking isolated *P.patula* as severely as plantations (Gibson and Jones 1977).

The opposite view, that large scale establishment of even-aged stands does not increase the risk of pests and diseases, has been propounded by Chou (1981). Chou was defending the planting of *P.radiata* in New Zealand where monospecific planting has been highly successful on a limited range of environmental conditions. Briefly the points that he has made are:

- there is no such thing as a generalised or typical epidemic, therefore there is no reason to believe that a generalised prescription recommending mixed plantations will be effective in preventing epidemics;

- in certain circumstances indiscriminate mixtures can increase risk, for example if alternate hosts for pests or diseases are introduced or if a mildly susceptible species is mixed with a very susceptible species. This point is also made by Perry and Maghembe (1989);

- some pathogens attack a wide range of hosts. *Phytophthora cinnamomi* is known to affect 444 species in 131 genera and 48 families including both angiosperms and gymnosperms. *Armillaria* spp.contain a large number of strains that are relatively host-specific but with a host list that includes 677 species in 276 genera it is unlikely that mixtures will be completely effective as a barrier to the spread of these pathogens unless there is good data available on the relative susceptibility of the species to be included in the mixture;

- diversification of species implies diversification of the effort to control diseases and pests and a dilution of the effort applied to any one species and therefore an increase in the risk for that species. Where, as a result of a diversification policy, planting material has to be imported, that in itself represents a risk of introducing disease and pests;

- pure even-aged stands facilitate human intervention for the control of pests and diseases. On the other hand in mixed stands, particularly all-aged stands, where selective felling is a management tool, the likelihood of damage to standing trees and the subsequent risk of entry by pathogens may be increased.

Role of mixed planting.

Although diversity of species may contribute to stability in natural stands, it cannot be assumed that species diversity must necessarily provide stability in all artificial stands. A legitimate objective of the management of plantations, whether industrial or non-industrial, is the maximization of growth, or the production of other specified outputs, onto the most valuable species for the objectives specified. This, for a variety of economic and industrial reasons, reduces the number of species considered for planting. What is generally agreed is that though a reduction in diversity can result in an increased risk of pest and pathogen damage, not nearly enough is known about the mechanisms by which diversity does create stability (Boyce 1954; Chou 1981; Perry and Maghembe 1989). There is as a consequence a lack of knowledge on what species mixtures are desirable for controlling attacks by pests and pathogens, particularly in exotic plantations.

It is worth noting some of the situations in which mixtures have proved beneficial in controlling attacks by pests and diseases. The cerambycid borer *Phryneta leprosa* attacks *Milicia (=Chlorophora) excelsa* through blisters resulting from sun scorch in even aged plantations. It has caused losses in trial plots in Tanzania and very severe and widespread losses in Zaire (Gibson and Jones 1977). Shading will control sun scorch and an admixture of other species will provide shade when the *M. excelsa* plantations are established.

Phytolyma lata causes leaf gall on *M. excelsa* and can be very damaging, but the insect has a limited range of dispersal. However, control of the insect is only achieved when the host tree is dispersed in a matrix of other species to such an extent that one is bound to consider the proposition stated in the 1939 Dehra Dun conference: if the nurse species has to form the major portion of the crop and is of low value, then another crop should be considered; if the nurse species is of equal value to the main species, there is little point in planting the main species (Indian Forest Service 1939).

The stem borers *Hypsipyla grandella* (in the New World) and *H.robusta* (in the Old World) are notorious for the damage that they cause to the leading shoots of young trees in the sub-family Swietenioideae of the Meliaceae, most of which are valuable timber trees.

Table 2 Host Genera of the stem Borers *Hypsipyla* spp.

Africa	Asia	South America
Lovoa	*Toona*	*Swietenia*
Khaya	*Chukrasia*	*Cedrela*
Entandrophragma	*Soymida*	*Carapa*
Carapa		
Pseudocedrela		
Guarea (attack recorded though in Melioideae, Styles 1991).		

Xylocarpus spp which are in the sub-family Swietenioideae have not been reported as being attacked (Styles 1991) and in South America *Guarea* is reputedly not attacked (Whitmore 1976). To some extent the two *Hypsipyla* species are specific to the tree species of their own zones. For example, *Toona ciliata*, which is heavily attacked by *H.robusta* in Australia, is not attacked, or is only lightly attacked, by *H.grandella* in Costa Rica, where the native *Cedrela odorata*, on the other hand, is heavily attacked by *H. grandella* (Grijpma and Ramallo 1973). *H.robusta* attacks *Swietenia macrophylla* in India and Sri Lanka and *H.grandella* attacks *Khaya senegalensis* in Martinique (Grijpma 1973).

Shade is effective in reducing, but does not fully control, attack by *Hypsipyla* (Whitmore 1976). Shade is normally provided by other species either planted concurrently with the Meliaceae or in the form of residual stands into which the Meliaceae are line planted. Suitable mixtures have been investigated extensively in West Africa (Dupuy and Mille 1991); this is discussed more fully under Management in Chapter 5. But another species is not always required to produce the shade; *S. macrophylla* is being regenerated successfully at Sundapola in Sri Lanka under the shade of mature trees mostly of the same species (Muttiah 1991).

The establishment of Meliaceae susceptible to *Hypsipyla* under a nurse crop to provide shade is an obvious example of the use of mixtures in industrial plantations, but it has to be noted that in francophone West Africa, where most recent work on the silvicultural management of Meliaceae has been carried out, the decision has been taken not to plant Meliaceae (Cossalter 1991). On the other hand the Sundapola mahogany plantations were established very successfully in mixture and in the Solomon Islands it is proposed to establish *S. macrophylla* in a matrix of *Securinega flexuosa* (Solomon Islands 1988 a and b).

In Kenya a canker on Cypress *(Cupressus macrocarpa)*, is caused by *Seridium unicornis* (the imperfect state of *Rhynchosphaeria cupressi*). This fungus gains entry through wounds and pruning scars, but has a limited range of effective dispersal and it would therefore appear that the proximity of trees in a pure plantation must contribute to the spread of the disease. Mixed planting of *Cupressus macrocarpa* and *Grevillea robusta* has been tried in Kenya (Graham 1945 and 1949), but the management of such mixtures has proved difficult resulting in poor form (butt sweep and lean) of trees of both species. There was little evidence that the mixture controlled the disease. Eventually the decision was made to replace *C. macrocarpa* with *C. lusitanica,* a less vigorous species, but which is less susceptible to cypress canker and which has a better form.

In India and Pakistan the insect *Hoplocerambyx spinicornis* has changed from being an inhabitant of felled logs and moribund trees of *Shorea robusta* in natural forests to attacking healthy mature trees when that species was extensively established in pure plantations; the change in habits has been attributed to the improved opportunities for reproduction provided in plantations (Gibson and Jones 1977) and may owe something to increased food supplies and even to stress arising from planting the species on an unsuitable site. In Nigeria *Hecophora testator,* an insignificant pest of the natural forest, caused widespread damage to pure plantations of *Nauclea diderrichii* (Gibson and Jones 1977). Mixtures of *Nauclea diderichii* with *Lovoa trichilioides* and *Entandrophragma utile* have, however, been successful (Lamb 1991; Lowe 1991).

In Africa, at least, the most important and largest number of examples of insect pests attributable to the establishment of monospecific plantations are defoliators, and to a lesser extent borers (Gibson and Jones 1977). *Nudaurelia cytherea, Orgya mixta* and *Pachypasa capensis* were noted as examples of defoliators of *Brachystegia* woodland, which have over a period of years adapted to and cause extensive damage pine plantations; *Buzura edwardsi* is another example. But there is no indication that mixed plantings will reduce the attacks. In Malawi an attack of *Plagiotriptus pinivora* caused sufficient damage to pine plantations to justify control by aerial spraying (Gibson and Jones 1977).

Conclusions **on** insects **and** diseases.

The evidence of serious losses due to pests or diseases resulting from monospecific plantations is confusing. Gibson and Jones (1977), while stating on the one hand that the most pessimistic forecasts of traditional foresters on the dangers arising from forest monocultures have been fully vindicated, were also able to give as their opinion that pest and disease problems engendered by forest monocultures have seldom reached the catastrophic levels of certain pests and diseases of natural forests or tree crops grown for non-commercial ends. This situation may be changing as more pest species are introduced; for example three introduced species of conifer aphids have devastated Pines and Cypresses in eastern and southern Africa. The pine woolly aphid *Pineus pini* and the pine needle aphid *Eulachnus rileyi* were first noticed in 1968 while the cypress aphid *Cinara cupressi* was discovered in 1986. They now constitute a major threat to the future of conifers in the plantation programmes of the region, and the cypress aphid is also attacking the native conifers *Juniperus procera* and *Widdringtonia nodiflora* (Ciesla 1991; FAO 1991a).

It is to be noted that though most work on forest pathology and entomology is related to intensively managed stands and little is known of the role of pests and pathogens in the ecosystems of most natural forests in the tropics, yet the knowledge on forest plantations still lags behind the knowledge of these problems in agrisystems (Gibson and Jones 1977). Management that is based on a policy of "high input/high output" will insist on answers being found which do not greatly lower outputs and will ensure that finances are made available to find solutions. These solutions are likely to be either in the form of biological or chemical control or tree breeding to develop resistant strains or through a change in the species. It is of interest that Peace (1957) discounted the possibility of spraying forests to control diseases, but less than thirty years later aerial spraying to control *Dothistroma* blight was standard practice in many young *P. radiata* plantations in New Zealand (Chou 1981). It is also to be noted that the "low technology" solution of mixed planting to control *Hypsipyla* damage in francophone West Africa has apparently been abandoned.

Where uniformity of product is not so important and where less intensive management is practised, as in many fuelwood plantations, then a "low input/low output" management policy will be more appropriate and mixed plantings are one of the possible solutions. In this case the establishment of mixed plantings may be used for "insurance" purposes, while most knowledge is likely to be available on appropriate mixtures of indigenous species. In the low technology situation where maintenance of ground cover is of as great or greater importance than economic return mixtures may be considered as an insurance against complete failure.

It is recognized that until more is known about the mechanisms and strategies of pests and diseases and of their predators in the natural forest there may be few, if any benefits to be derived from the use of mixed species plantations to prevent or control the spread of insects or diseases, and there may even be disadvantages, for example,by providing alternative hosts or possibly acting as barriers to predators (Chou 1981; Perry and Maghembe 1989).

A major problem is the fact that modern communications facilitate the transfer of pests and diseases round the world. Protective systems which have been evolved in natural forests are very vulnerable to exotic organisms. It is unlikely that mixtures will be effective in controlling epidemics of exotic origins, therefore the best hope of control is the introduction of natural enemies, breeding for resistance or chemical control - or a combination of these. Chemicals are more easily applied in pure plantations but the need to protect the environment from pollution and the high cost makes this tactic a measure of last resort.

3.6 CONCLUSIONS ON ENVIRONMENTAL IMPACT

Environmental impact has been considered under the separate heads of soil, climate, fire, wildlife, pests and diseases. These factors, and others, interact to form the forest ecosystem and it should be the objective of the forester to ensure that it is resistant to agents of change but that at the same time the site retains its productive potential. The occurrence of devastating attacks by pests and diseases are often a symptom of poor management decisions, such as species selection or delayed thinning, and the solution lies in good forestry practice. In these circumstances where basic management errors have been made it is unlikely that a mixture will be of any help in controlling an attack. Mixed plantations are likely to be beneficial in projects managed extensively and where there may be unpredictable pest or disease attacks or climatic events. Mixed plantings are then an insurance against complete failure and they may be effective in reducing the vulnerability of an indigenous species to an indigenous pest or disease, providing that it has been properly managed - see above - but the degree of dispersal required may call in question the feasibility of managing that species intensively.

The possible deterioration in site fertility is in some ways a more insidious problem in that without a well maintained network of Permanent Sample Plots the problem may go unnoticed until fertility has been seriously impaired. Even with a good monitoring system it is unlikely that site deterioration caused by a particular type of plantation, as indicated by changes in yield, will be detected until the following rotation. Though the detailed functioning of soil micro-flora and micro-fauna is not well understood in the tropics, provided fertility problems are recognised in time the action needed to prevent loss in fertility are well known:

- retention of topsoil and organic matter when establishing plantations;
- replacement of nutrients and restoration of physical condition after harvesting, and
- ensuring that crop nutrient requirements do not exceed the site capacity by, for example, overstocking or as a result of litter build up.

Mixed plantations are a management tool for influencing soil conditions by providing ground cover to protect against soil erosion and moisture stress or to ameliorate topsoil conditions to favour beneficial micro-organisms. The mixture may be achieved by planting or by allowing a natural understorey to invade under an open canopy. Plantation management, based on clear objectives, can also promote the conservation of animal and other genetic resources.

Fire is a serious and increasing hazard to plantations, with heavy direct and indirect costs. Investigations into the potential of mixtures of species to reduce the incidence of fires or to slow down their spread have not been documented but would appear to be worth further study.

Because of the unpredictable nature of epidemics and climatic change the maintenance of genetic diversity in a plantation is essential. Diversity may occur at different levels; there is both diversity between species and within species. Total diversity gives the stand a better chance to evolve to cope with new conditions and also gives some insurance against complete loss. Diversity, however, can also be achieved in the broad sense by having a mixture of blocks or compartments rather than a mixture in the narrow sense. The decision whether to have mixed plantations in the narrow sense must depend on the objectives of management. Intensive management of industrial plantations will probably indicate pure plantations, while more extensive management of, for example, fuelwood plantations may benefit from mixtures and if the prime objective is rehabilitation then mixed planting will frequently be called for. But it must never be forgotten that management objectives should only be set after due consideration of the potential and limitations of the site and that objectives may have to be further modified in the light of species available for the site. The maintenance of long term sustainability and site fertility is all too often given insufficient emphasis in plantation schemes (Lundgren 1980).

4. NON-INDUSTRIAL PRODUCTS AND SERVICES

Mixtures have not historically been used in plantations for the production of industrial wood products, but have generally been thought of as more suitable for non-industrial products or the provision of environmental services. The special case of non-industrial products and services is therefore considered in this chapter.

Non-commercial uses

It is now widely acknowledged that forests provide a wealth of products which are used by local communities living in or near them. Though some of the products arise from sources outside the forest - in compound farms, outlying farms or as fodder trees on farm boundaries - many are collected as a "free good" from the forest. It is evident that farmers have knowledge of the site and silvicultural requirements of the species grown in compounds and outlying farms. But these species are usually raised in small plots in an agroforestry environment and have been excluded from consideration in this study. In Nigeria (and probably most of the African humid tropics) the knowledge of the silvicultural requirements of the species collected from the forest is often lacking (Okafor 1977). No reference was found to the establishment of mixed forest plantations in the humid tropics by local communities for the provision of the range of goods used by them or of their deliberate management of natural forests. This should not be taken to imply that there has been a complete absence of traditional management by local communities in tropical forests. Such management systems have existed but have not been recorded. In countries that have passed through a period of colonialism traditional management systems have often been made unworkable by foresters and administrators, for instance by the creation of forest reserves and the imposition of forest rules which have ignored local management systems. Traditional management of natural forests has tended to concentrate on the organisation of the distribution of an available resource rather than on the manipulation of the ecosystem in order to benefit any particular component species. Where human population has created increased pressure on the forest then traditional management systems tend to break down. In the countries in the sub-tropics, such as Nepal, there is a better history of controlled exploitation of forests by local communities, but again management has not really involved the manipulation of the forest to produce specific end products.

An added problem is that in many societies in the tropics there is little respect for the natural forest, because the first requirement is to have land for cultivation and because forest products are regarded as a free good. Although the forest's worth may be appreciated, there is little feeling of individual responsibility for protecting the forest because benefits tend to be so widespread. Artificially established plantations are often treated with more respect than natural forest even when it is under management.

It is generally recognized that the loss of natural forest in the humid tropics deprives local communities of many products, but there is insufficient knowledge to establish and maintain the plantations provide those products. Forestry projects have been criticized for replacing polyspecific natural forests with monospecific plantations that do not produce the many other products to be found in the natural forests. But if there is any pressure for agricultural land, the solution of protection and low intensity management of the natural forest is usually impossible. Since there is currently inadequate knowledge to establish mixed forest plantations to meet the requirements of local communities, the only possibility left is to protect and manage an area of natural forest in combination with a commercial, possibly monospecific, plantation project. The heavy requirements for fuel and poles can then be met from the plantations, while the natural forest provides other products. Much more needs to be known about the silvicultural requirements of the large numbers of fruit trees, medicinal trees and herbs etc that the local community use, but which may be only locally valued, before it will be possible to establish mixed plantations which can also be used for the satisfaction of such needs.

Fuelwood and poles.

By 1980 some 39% of plantations in Africa, Asia, South America and the Pacific Islands[1] were classified as non-industrial (FAO 1988). In the estimate of the area planted between 1981 to 1985 the proportion increased to 46% (FAO 1988).

Most non-industrial plantations are established with the objective of producing poles or fuelwood. Usually the production is for a local market and a minimum of processing will be involved. There is, therefore, less incentive to use highly mechanized harvesting techniques and as a consequence plantations can be established on steeper and rockier sites, unsuitable for industrial plantations. Mixed plantations may thus be very suitable for the production of fuelwood and poles, provided suitable species are selected both for the site and to meet the user's requirements, but unfortunately the less fertile sites that are often available may limit the choice to a single species. The experience in Nepal is described in more detail later in this chapter.

Fodder.

Browse and fodder for livestock are at a premium in any climate that has a long dry season. Grass in woodland can be grazed and forests, particularly on the hills with a higher rainfall, can be reserved for dry season fodder; grass can also be cut and carried to the livestock. Grass, however, dries up and dies early in the dry season, while tree foliage and fruits, for example *Acacia* pods, can remain palatable and nutritious much longer. But the ability of a tree to retain its leaves or pods varies with the species, therefore to ensure a supply of fodder throughout the dry season a mixture of species is essential in order to have a sequence of species from those that shed their leaves early in the dry season to evergreens, such as some of the oaks (*Quercus semecarpifolia* for instance) and *Ilex* spp in the Himalayas. Relatively little has been published on the management of tree fodder crops, but some work is being done in Nepal (Gilmour et al 1989;1990; Applegate and Gilmour 1987; Mohns et al. 1988).

Rehabilitation of degraded sites.

The afforestation of degraded sites in order to revegetate the area and to regain a good soil structure is increasingly being recognized as a forestry

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[1] Excluding South Africa and also China and Argentina for which there are no detailed data.

objective in itself. In these circumstances low growing trees and shrubs, which can provide ground cover, may play as important a role as large trees. Nevertheless it is often difficult to protect and manage such sites, particularly if there is any pressure for alternative (even if unsustainable) use for the land, unless it is possible for local communities to benefit from tree products on the site. Therefore a mixture of ground cover and soil forming species with fodder, fuelwood, pole and timber species is desirable.

In Brazil experimental work has been done on rehabilitating degraded sites paying particular attention to the ecological requirements of each species and the position in the ecological succession (Nogueira 1977; Durigan and Nogueira 1990). Results have been generally good but an analysis of subsequent natural regeneration indicates that there will be a progressive tendency to a reduction in species diversity (whether natural or induced) by in succeeding generations.

In India afforestation of dolomite mine overburden (Ram Prasad and Camire 1988) has been reported. *Acacia auriculiformis, A. campylacantha, Gmelina arborea* and *Pongamia pinnata* showed slightly better height and diameter growth when mixed with bamboo; the growth of *Albizia procera* was somewhat retarded by bamboo. In Madhya Pradesh a bauxite mine site has been revegetated with *Shorea robusta* in mixture with *Grevillea robusta, Eucalyptus camaldulensis, Toona ciliata* and *Pinus kesiya* (Ram Prasad 1988); the reason for selecting this very diverse mix of trees is not clear and no information was given on the success of the mixtures.

The shrub *Hippophae rhamnoides* (sea buckthorn) is frequently planted in mixture with forest trees in China. It is resistant to drought and cold and is valued for soil conservation and improvement due to its nitrogen-fixing ability as well as for its fruits (which are rich in vitamin C) and other products such as fuelwood, fodder, medicines and oil. The shrub is mixed with *Populus* spp. in soil conservation works and in shelterbelts, but although 60 000 ha of the species are planted yearly there is no estimate of the amount planted in mixture, nor of the possible relative advantages such mixtures might have over pure plantations. The tree *Robinia pseudoacacia* (false locust) is also used in mixture with poplar in China. In neither case have records been found of improvements in the growth of the main tree crop, nor of increased production from the site, when compared with the poplar grown alone.

Shelterbelts and windbreaks.

This function has been mentioned in the section on climate. Because windbreaks are usually planted to protect crops, they need to be narrow in order to minimize the area of land taken out of agricultural production, but in order to reduce turbulence a windbreak should be triangular in cross section rather than a tall straight sided barrier. A mixture of species of varying heights at maturity will achieve the desired cross section shape and are also likely to filter the wind better than a dense planting of a single species. In Kano, Nigeria, shelterbelts were planted with eight central rows of *Eucalyptus camaldulensis* and four rows of another species on either side. The other species included *Acacia* spp, *Azadirachta indica* and *Anacardium occidentale* (suited to the more humid sites), the intention being to fell half the width at age eight and then alternative halves every four years to produce poles and firewood (Lowe 1991).

Urban and periurban planting.

Trees in cities improve the microclimate and cut noise transmission. Periurban planting is not only an important amenity, but in arid and semi-arid areas can reduce wind and dust in the city. Both urban and periurban plantings are at risk from the unpredictable effects of air pollution. A mixture of species is desirable both from the amenity point of view, to avoid the appearance of uniformity, and in order to increase the chance of survival of some tree cover in the event of biotic or abiotic damage. The severe impact of ozone pollution on natural forests of *Abies religiosa* in the hills round Mexico city has been noted earlier as has the damage done to *Pinus jeffreyi* in the San Bernardino Mountains of California where incense cedar (*Calocedrus decurrens*) and white fir (*Abies amabilis*) have survived largely unscathed.

Some examples of non-industrial plantations

Community forestry in Nepal

There has been a tradition of controlled exploitation by the local communities in the hills of Nepal, but controls have broken down and excessive exploitation has reduced many hillside forests to over-grazed grassland carrying a few heavily lopped stumps. A reforestation programme was initiated in the nineteen seventies; much of the early planting was with native chir pine (*Pinus roxburghii*). It was found that once a site was closed to grazing there was a good regeneration of hardwoods such as *Schima wallichii* from old stumps, from suckers and later from seed. These hardwoods have very much higher value to the local communities for fodder, firewood and farm implements than pine has. Since 1979 the Nepal/Australian Forestry Project has been running experiments to see how pine/hardwood mixtures can be managed to produce different end products and to determine their yields. The options tested have been to thin to favour the pines or the hardwoods in various proportions or to coppice the hardwoods (Gilmour et al. 1989,1990; Applegate and Gilmour 1987; 1988; Mohns et al 1988). Enrichment planting has been included and the whole operation is more a matter of enrichment planting into grossly over-exploited natural woodland than establishment of mixed plantations. It is too early to draw definite conclusions, but there are some general lessons to be learned from this experience which can be applied to the community forestry elsewhere and in particular to assisting local people in making the choice between mixed or pure plantations:

- it is essential to include the local communities in the management and planning of the established woodlots;

- if the community is to make an informed contribution to management planning it must have a clear idea of the options, therefore demonstration plots are required;

- prescriptions must be simple, but there is no particular problem in manipulating the species mixtures to the extent of varying the proportion of pines and broadleaf species.

Rattan.

Rattans, which are a family of climbing palms, are exploited both to satisfy the needs of local communities and as a major export crop from Indonesia and Malaysia in particular. Of the small cane rattans only *Calamus caesius* and *C. trachycoleus* are planted extensively in the rainforest belt of this region. They are cluster rattans and *C. caesius* has traditionally been treated as a crop of shifting cultivation, being harvested completely at age seven to ten years and again at the end of the fallow period at about age fourteen. If, however, the clusters are harvested selectively in alternate years, they can be managed on a sustained yield basis for many years (Dransfield 1979).

Canes are usually cultivated in secondary forest, but they have been raised successfully in abandoned rubber plantations and even in a *Pinus oocarpa* plantation and a *Shorea robusta* plantation in Bangladesh (Davidson 1986). The manipulation of the shade is critical to the production of quality rattan; too much shade, for example under *Dillenia* spp., results in poor growth of the rattan, but with longer internodes, which is a desirable feature. In Sabah, East Malaysia the yield of *Calamus trachycoleus* after 11 years has been estimated at 2.5 tons/ha/year with a sale value of US$800/ton unprocessed and US$1 500/ton processed (Dransfield 1988).

C. manan is usually grown for the production of large canes; this species is not a cluster rattan and does not shoot from the base after cutting and therefore can only be cut once. Other large cane rattans which do form clusters, e.g. *C. inermis* or *C. merrillii* from the Philippines are possible alternatives. Another problem with *C. manan* is that the its weight (it can grow to 180 m in length) can break supporting trees. Other rattans are grown in India and Sri Lanka and there is even one African species of rattan.

Rattan would appear to offer attractive financial returns, up to about US$3 500/ha/year gross after only 11 years, with few management expenses. It has to be grown in mixture, but to what extent the other species of the crop can contribute to returns is not clear. The options would appear to be either to consider the rattan to be a component of the early secondary successional stage of the ecosystem and to accept that it will be replaced in later stages, or to attempt to manipulate the canopy in order to retain it throughout a longer rotation, or to maintain the plantation in an early stage of succession to favour the rattan at the expense of other components of the crop. There is scope for further investigation.

Sandalwood (see also Appendix 4)

Sandalwood is a root hemi-parasite that can grow in association with a wide range of hosts, including grasses. The genus occurs in India, Australia and the Pacific basin. There are fourteen species, but the most valuable and one of the most vigorous is *Santalum album* which occurs naturally in India and in West Timor, Indonesia; this species is now being planted in Western Australia and also in many of the Pacific Islands, where indigenous species have been heavily exploited.

Sandalwood is one of the most valuable timbers on the world market. It is used for carving in India for which use it can fetch up to $US 9 400 per tonne. Australian grown sandalwood is mostly sold on the Far East market for incense and even wood chips and powder can command prices of about $US 2 300 per tonne. Sandalwood oil sells on the European and North American markets at $US 1 500 per kg.

It has been found that establishment can be improved if a primary host is used in the nursery, but that in the field the sandalwood and its primary host should be planted out near to a secondary host, usually a larger, more vigorous species. The primary host should be a low growing shrub, such as *Cajanus cajan* or *Sesbania grandiflora*; *Acacia* spp, *Albizia* spp and other legumes such as *Bauhinia biloba*, *Dalbergia sissoo* and *Terminalia* spp have been found suitable, but *Pinus caribaea* and *Araucaria* spp have been recorded as giving poor results.

Conclusions on non-industrial products and services

The inclusion of species that provide non-industrial products and services in plantations is an important way in which the needs of rural people for many forest products can be met and in which they can be involved in the production of goods for use elsewhere, such as in the growing of rattan or sandalwood. It is likely that there is a far wider range of such species than has been reported here, which suggests not that the demand for their products does not exist but that they have not been adequately investigated with a view to incorporating them in single species plantations as a form of enrichment planting.

5. THE MANAGEMENT OF MIXTURES.

There are two important sources which review the classification of mixtures, methods of achieving them and their success:

- The Indian Forest Service in the fourth and fifth Silvicultural Conferences in Dehra Dun in 1934 and 1939. The minutes of these conferences give an extensive account of experiences and logical guidelines for establishing forest plantations in mixture in the Indian subcontinent.
- The Centre Technique Forestier Tropical has studied the subject in West Africa and various reports and papers have been brought together in a chapter of FAO Forestry Paper no. 98 - *Les Plantations à Vocation de Bois d'Oeuvre en Afrique Intertropical Humide* (Timber Production Plantations in the Humid Tropics of Africa) (FAO 1991b). A classification and criteria for selecting and managing mixtures are given.

These two sources are complementary and come to similar conclusions. The following classification is drawn from both sources.

A Classification of mixtures.

No classification of plantation mixtures is entirely satisfactory, since classes of mixtures are not discrete, but tend to grade from one to another in a spectrum, depending on site and the degree of silvicultural intervention. The following classification, based on stand structure and the duration of the mixture relative to the rotation, is proposed:

1. Two-layered canopy.
   1.1. Temporary mixture, end result monospecific.
   1.2. Permanent, end result multi-specific.

2. Single-layered canopy.
   Generally permanent mixture, end result multi-specific.

In general reference will be made to mixtures of two species; more complex mixtures are possible but the management of even two species in a plantation is not easy and each additional species compounds the difficulties.

1. Two layered canopy.

1.1. Temporary mixtures, designed to become monospecific before the end of the rotation.

- Nurse Crops are used to bring a more valuable species through a difficult establishment stage. The most common circumstances in which they are used are to protect against adverse climatic factors - frost, insolation - or to deter insect attacks. In temperate zones the use of nurse crops to give frost protection is well known and they are of use for this purpose in parts of the subtropics such as the Himalayas. In the tropics the use of fast growing trees to nurse valuable species of the family Meliaceae and other species such as *Milicia (=Chlorophora) excelsa* through the stage in which they are at risk of attack from shoot borers is common. Few references to investigations into the effectiveness of this strategy were found, but the borers are thought to be inhibited by shade. The Sundapola *Swietenia macrophylla* (mahogany) plantations in Sri Lanka are a good example of the successful use of nurse crops, though the opinion in the Dehra Dun conference (1939) was that teak:*Swietenia macrophylla* mixtures were not successful in India and Sri Lanka. The pure mahogany plantations of Fiji and Martinique were, however, successfully raised without the benefit of a nurse crop and evidently without large-scale attack by borers.

An understanding of the succession of species in the local ecosystem will often help in the selection of nurse species. *Milicia (=Chlorophora) excelsa* and *Entandrophragma grandifoliola* were established successfully in fire prone *Terminalia* woodland using *Phyllanthus discoideus* as a nurse crop (Dawkins 1949). After forty years, though the site has suffered several vicissitudes, the *M. excelsa* and *E. grandifoliola* are reported to have done well on moisture receiving microsites.

In Nepal there is an interesting variation on nurse crops. There the planting of pines in village afforestation schemes defines very clearly the area to be reforested and thereby makes the protection of the site against unplanned cutting by the villagers and unmanaged browsing by their cattle simpler and more effective. Often there is no need to fence. As a result there has been satisfactory regeneration of the more valuable hardwoods under the pine canopy. Subsequently, the pines can be removed or allowed to grow on as a further component in a mixed hardwood stand (Gilmour *et al* 1990).

- Silvicultural reasons, in order to improve the form of the main crop. This may be an effect of spacing, and it has not been scientifically tested, but the form of *Pterocarpus dalbergioides* in the Andaman Islands is considered to be improved when the tree is grown through an overstorey of *Lagerstroemia hypoleuca, Terminalia bialata etc. Dalbergia latifolia* is similarly improved by growing through an overstorey (Indian Forest Service 1939).

- In-fillers can be used if there is a shortage of the main species, or the main species is expensive or difficult to establish. In that case the main crop can be planted at wide spacing in a matrix of cheap in-fillers which can suppress weeds, supply side shade to the main crop or provide ground cover to protect the soil. In Indonesia *Altingia excelsa, Schima wallichii* var. *noronhae, Eugenia polyantha* were recommended for planting under *Toona sureni*, in order to provide ground cover with wood production as only a secondary objective (Grutterink 1930).

In many respects these three functions of nurse crops, silvicultural improvement and in-filler can be achieved by enrichment planting in forests in the humid tropics. The naturally occurring low value residual species in cut-over forest have a nursing, cultural or in-filling function, though the advantage of the latter is seriously reduced by the prevalence of climbers on many sites. It is hard to find examples where enrichment planting to establish industrial plantations can be considered an unqualified economic success. There was some optimism that trials involving group planting of *Maesopsis eminii* and the exploitation of the residual forest for charcoal would be profitable (Earl 1968), but there have been no recent reports of this work. On the other hand, introduced species, such as *Albizia chinensis, Melia azedarach, Milletia dura* and in particular *Maesopsis eminii* have invaded the natural forest in the East Usambara mountains of Tanzania, where they are now competing with the indigenous species (Binggeli and Hamilton 1990). However, where the prime objective is not so much wood production as the maintenance of a diverse ecosystem, enrichment planting is to be recommended because the soil is not put at risk during the establishment process.

- Early economic returns can sometimes be obtained through the use of mixtures when the main crop is a valuable, but slow growing, shade bearer having no value as thinnings. An early return from an admixture of a fast growing species can make a project economically more attractive. In India and Myanmar the planting of *Xylia dolabriformis* with teak was not considered a success (Indian Forest Service 1939), but as the teak which tended to suppress the *X. dolabriformis* was rather more valuable the failure was not too serious, especially as the mixture had the effect of spacing the teak out at a period when it was customary to plant teak too close. In Nigeria the establishment of *Lovoa trichilioides* and *Entandrophragma utile* with *Nauclea diderrichii*, which can be exploited for poles at the age of 15 years, was considered a success (Lamb 1991; Lowe 1991). In the Solomon Islands experiments have been instituted for raising *Swietenia macrophylla* in a matrix of *Securinega flexuosa*, which has a ready market as house poles at age five or six and is also expected to reduce the incidence of *Hypsipyla* shoot borer in the Mahogany (Solomon Islands 1988a).

The timing of the removal of the temporary crop and the care needed to ensure that the main crop is not damaged during removal of the nurse trees is of great importance.

1.2. Permanent mixtures

- Understorey for soil improvement. The necessity for maintaining the organic matter content of the topsoil and the conditions under which it can be expected to be depleted, for example through the build up of litter (Morris 1986) or litter removal by fire under teak (Bell 1973), have been noted in the section on soils. Some species have leaves that break down more easily and provide a better environment for microfauna and flora which are the main agents for converting litter to organic matter in the soil. The mixture of other species with *Cordia alliodora* in Costa Rica has been shown to increase the rate of decomposition of the *C. alliodora* leaves markedly (Babbar and Ewel 1989). The introduction of understorey species into the teak plantations in Indonesia in the early part of the twentieth century was largely motivated by a desire to improve soils or hydrological conditions, though the production of more saleable wood from the understorey was also considered an essential requirement of understorey planting. Opinions were sharply divided on the necessity or utility of planting mixtures. By the nineteen thirties evidence had been collected to show that the planting of mixtures was unprofitable in economic terms (Hart 1931a) and that an economically better, but ecologically similar, result could be achieved by encouraging a natural understorey (Kunst 1918). It was suggested that the beneficial effects of an understorey of *Leucaena* sp. could be attributed to the effects of the cultivation rather than to the species (Hart 1931b). In north-east Zambia the lack of a deep litter layer under twenty year old *P.kesiya* (18 m. tall; 23 cm dbh; soil pH 6.2) was associated with an open canopy and a good ground cover including *Desmodium ascendens* var. *robustum* and *Sphenostylis marginata* and the presence of earthworms (Lawton 1991).

In Trinidad the practice arose of close planting teak and in consequence there was an increased incidence of fire because the deciduous teak leaves accumulated on the forest floor without decomposing. As a result fire-tender species were eliminated which in turn resulted in the almost complete loss of organic matter in the topsoil and serious erosion. Previously the teak plantations had been established at a wider spacing and with an admixture of other species. In those plantations the teak leaves decomposed much faster and the forest floor, being much less prone to fire, provided conditions suitable for natural regeneration of local trees and shrubs. There was more ground cover, better soil conditions and less erosion (Bell 1973).

The use of N_2-fixing trees, particularly acacias, is often advocated e.g. *Acacia auriculiformis* which may be coppiced under *Eucalyptus exserta* in China (Barnes 1991, Kaeokamnerd 1991) or the mixtures of poplars with *Hippophae rhamnoides* or *Robinia pseudoacacia* (see Chapter 4). Soil conditions are improved through the growth of the N_2-fixing species and the utility of the plantations to people is improved through a wider range of products, but there is little evidence from the tropics that the main crop is significantly improved. There are, however, well-documented instances of N_2-fixing operating beneficially on the growth of one of more components of a mixture in North America.

2. <u>Single layered canopy</u>

By this is meant the maintenance of a mixture of two woody species, both of which are dominants. This mixture is usually permanent for the duration of the rotation, but there is always an option to convert to a single species thereby making the mixture temporary. The reasons for attempting a single layered mixture include:

- Synergy. Two species growing together may give a higher yield than the mean of those two in separate pure plantations. The mixed species effect has been noted in Scandinavia with pine and spruce (Jonsson 1961) and in the beech/oak forests of Belgium, Germany and France. In Queensland it has been the practice to plant *Pinus elliottii* with *Araucaria cunninghamii*; there has been a positive response in the *A.cunninghamii* growth, but the sites have been outside the normal range of that species and the practice has been discontinued (Applegate 1991). A mixture of *Bombax malabaricum* and *Acacia catechu* has been noted to have better growth than either species alone in India (Indian Forest Service 1939).

The *Eucalyptus/Albizia* mixture in Hawaii (DeBell et al. 1985) is a tropical example of apparent synergy associated with N_2-fixing; somewhat unusually in this case the N_2-fixing species is in fact larger and faster growing than the "main species". This example is discussed more fully later in this chapter.

- Reduction in attacks by pests and diseases. This is covered in detail in Chapter 3. Permanent mixtures only appear to act effectively as a barrier to diseases and pests when the valuable trees to be protected are highly dispersed as in the case of *Milicia (=Chlorophora) excelsa* liable to attack by *Phytolyma lata* (Gibson and Jones 1977). There are instances where mixtures may actually increase the likelihood of attacks, e.g. the introduction of an alternate host species, and therefore mixtures cannot be assumed to provide added protection on all sites or for all species.

- Wind. It is possible that in temperate zones the mixture of e.g. beech with larch may increase resistance to windthrow, but there is little evidence from the tropics. In South Africa it was hoped that the introduction of the supposedly deeper rooting *Pinus radiata* into stands of *Acacia melanoxylon*, which is liable to windthrow, would improve stability. This was not a success (de Zwaan 1981).

- Economic insurance. This is discussed further in Chapter 7. If it is uncertain which species will perform best on a site, or if there is a risk of an unpredictable event - late frost, wind, drought - then it may be justifiable to plant two or more species (Indian Forest Service 1939, Heybroek and van Tol 1985). In this case the mixture is often temporary because it will be found that a monospecific stand has developed by the end of the rotation and the mixture may well be redundant for the second rotation, because information will have been gained on the site requirements for each species in the mixture (Heybroek and van Tol 1985). The mixture should be carefully matched to the site and a knowledge of the local ecosystem successional species is useful.

Silvicultural criteria for successful mixtures.

- In temporary mixtures the species should be compatible to the extent that the secondary species is not too demanding; for example it should not have too vigorous a crown, so that the two species can coexist for several years without intervention.

- In permanent single layer canopy mixtures there is a narrow range of sites, silvicultural characteristics and management options within which successful growth of mixtures is likely.

The site must be suited to both species (Jonsson 1961; FAO 1991b). The overlap of the site requirements of two species is often narrow. The range of sites on which two species can be grown together can be extended by silvicultural intervention, but that usually implies a reduction in economic profitability. This observation is merely an extension of the fact, already emphasised, that matching species to site is one of the first requirements of good forestry practice, whether the plantations are pure or mixed.

Silvicultural characteristics must be compatible; essentially this means that the two species should represent approximately the same stage in the secondary succession and should have similar crown characteristics. In addition the initial height growth should be comparable. Thus the mixture of slow growing *Khaya* spp or *Entandrophragma* spp with *Terminalia* spp or *Triplochiton scleroxylon* is unlikely to be successful, while mixtures of *Terminalia superba, T.ivorensis* and *Triplochiton scleroxylon* do have a chance of success (FAO 1991b).

The threshold at which competition starts and hence the density at planting, the maximum basal area and the timing and intensity of thinning also need to be similar.

In the tropics it is advantageous if the rotation ages are similar (FAO 1991b); this is because dominant trees in the tropics usually carry broad crowns and thinning operations can cause considerable damage to residual trees. In Scandinavia where crowns are relatively narrow, the removal of birch from pine and spruce at about 60% rotation age is recommended (Mielikainen 1985; Tham 1988).

Recently much thought has been given in Germany and other central European countries to putting plantation forestry onto a sound ecological basis. The criticism is made of many monospecific plantations that there is too great a risk attached to the attempts at narrow optimization of objectives (Brunig 1983), though the advantages of selection forests and "natural" management are probably overestimated (Kenk 1990). Mixed planting would achieve a broadening of objectives, but whether the advocated use of yield models instead of the more rigid yield tables is practicable in tropical polyspecific stands remains to be tested. The recommended policy of maintaining very open stands to encourage indigenous undergrowth achieves similar effects as the policy of heavy thinning, in order to put maximum growth on the most valuable stems, advocated on economic grounds in South Africa nearly forty years ago (Craib 1947). Examples of overstocked plantations of pine, cypress and teak are common in some tropical countries and the adverse effects on the sites are apparent; such effects are due to the management rather than to the single species composition.

Methods of establishing mixtures.

Mixtures can be established as intimate mixtures (that is, the species are mixed within the lines), by line planting (in which case each line is planted to only one species), which may be a combination of any number of lines of each species, or by groups. The combinations of mixtures within and between lines are described in some detail in the fourth Dehra Dun silvicultural conference (Indian Forest Service 1934). A general conclusion was that mixtures are extremely difficult to manage unless one component is clearly dominant and the other is a shade bearer that can survive in a semi-suppressed state; in other words a two layered mixture is easier to manage than a one layered mixture. Administratively line planting is the easiest to establish, but it is also the most difficult to manage technically, particularly if the species are not compatible. An example of a line mixture that did not succeed is the *Cupressus* spp./*Grevillea robusta* mixtures in Kenya (Graham 1949); the trees were not compatible and as a result the cypress neighbouring the *G. robusta* lines developed severe butt sweep. Intimate mixtures are the most satisfactory if the mixture has been planted as an "insurance", since the crowns of successful trees can expand into the space left by failures with the minimum edge effect. The natural occurrence of a mixture, however, is often as a mosaic of small groups in response to minor site differences.

In Zaire plantations have been established using groups of up to 37 plants at close (.5 m) spacing within the groups and 10 m spacing between the groups in a matrix of natural bush. The species used included a range of exotics such as eucalypts and pines, *Grevillea robusta* and *Acacia decurrens*; in one variant of the technique the species *Cupressus lusitanica, Eucalyptus grandis* and *Acacia decurrens* were mixed within each group. The species did not appear to have been selected with compatibility in mind. At 30 months the growth, as indicated by photographs, appeared good within the groups but there appeared to be no matrix and edge effects must have been large. The technique, based on Anderson's groups (Anderson 1953) was also proposed for Kivu and Ruanda (Pierlot 1955); no further reports have been noted.

A broad sense mixture (Chapter 1) was defined as being different species or provenances in neighbouring blocks. Mixtures of clones may be also defined in the broad sense of neighbouring blocks. An example of this form of mixing has been used in Aracruz, Brazil where clones of eucalyptus have been developed for each site type in the estate and there is a policy to ensure that out of a total of some 100 available clones a selection of 10 to 15 clones are used on each site in blocks of 5 to 30 ha (Burley and Ikemori 1988).

Management skills.

Mixed plantations require more intensive management than single species plantations so that while the basic skills may be the same for either type the management of the former requires greater attention to detail and has less room for error than the latter. The skills required may be summarised under three headings.

Clear objectives.

There must be a clear statement of objective for the mixture; whether it is soil improvement, increased yield by synergy, the reduction of adverse effects on wildlife etc. Only when the objectives are clearly defined can the field staff be expected to establish and maintain the mixture. Ideally, objectives should be held constant for a rotation but in fact one of the advantages of a mixture may be that if markets change then there is the flexibility to change objectives to meet the new demands.

Experience.

The point has been made that management of mixed plantations is a delicate operation (Dupuy 1986). Prescriptions can be established for guiding field foresters, but management decisions have to take account of small site differences and must be made in the field. The knowledge of what is the best treatment on any one site can only be obtained by experience and specifically experience of that site. The fact that some of the Sapoba mixed taungya plantations in Nigeria have eventually produced worthwhile mahogany trees despite discontinuous and inadequate management (Lamb 1991; Lowe 1991), does not invalidate the need for skilled management for mixed plantations to be economically successful.

Continuity of management.

In some parts of central Europe it is not unknown for a forest to be managed over many decades successively by three generations of one family. In this way experience is built up and passed on. By contrast in some countries it is civil service policy to transfer staff, even down to quite junior ranks every three years. In that way detailed experience of the silvicultural requirements of a forest can neither be obtained nor retained. Good management plans, records and the discipline to enforce their prescriptions can go some way to off-setting the effect of staff transfers. But though very long postings are usually impractical, without continuity of management and guaranteed finances the chances for successful management especially of mixed plantations are small.

The consequence of lack of management is likely to be a tendency for one species to gain dominance and to form monospecific stands or groups.

Some experiences **with** mixtures.

Some examples illustrate relevant points.

(a) The re-creation of natural forest conditions.

Tropical rainforests, if destroyed by man over an area larger than a small plot, will require several hundred years to reach a climax naturally (Adlard 1978). In Malaysia the dipterocarp demonstration plots at the Forest Research Institute, Kepong were established artificially in the nineteen thirties by planting under *Albizia falcataria* nurse crops. The plots were established on reclaimed tin mines or onto abandoned vegetable plots. This nurse crop was removed fairly soon, but over the years local species have regenerated under the dipterocarps. Now, sixty years later, some of these plots are believed to be a good approximation to the secondary succession of the natural forest that once grew on the site (Ng 1991).

In some areas of Brazil attempts have been made to re-create the natural forest. A wide range of species, mostly indigenous but including some exotics, has been planted on a few sites. These plantings have been studied to determine the species' ecological requirements and successional position (Nogueira 1977; Kageyama et al. 1990). In Sao Paulo an experimental planting of an area deforested for 50 years was, after 22 years, considered to be a vigorous semi-deciduous forest with trees up to 20 m tall. At Candida Mote, however, a study of natural regeneration in a 15 year old river bank planting showed that though 42 species had regenerated, 64% were *Nectandra megapotamica* and there is a strong tendency towards the development of a "homogenous" forest (Durigan and de Souza Dias 1990). A knowledge of local ecology and the species of each successional stage is helpful. In Uganda the selection of nurse trees for *Chlorophora excelsa* was based on a knowledge of local ecology (Dawkins 1949) and has apparently proved to have been reasonably successful. In Cuba a detailed classification of species by their successional stage and silvicultural requirements has been made for Sierra del Rosario (Canizares *et al* 1987).

There is no indication that the Brazilian plantings (above) are likely to produce commercial timber or that they were ever intended for anything but protection planting on river banks. But the Kepong dipterocarp plots, though they are in fact now being used as a recreational area, are carrying commercial timber of exploitable size. This one example has shown that re-creation of secondary forest conditions is possible in a reasonable time span in very small plots.

(b) A Mahogany plantation.

At Sundapola in Sri Lanka a mixture of mahogany (*Swietenia macrophylla*), teak (*Tectona grandis*) and jak (*Artocarpus integrifolius*) was established at the beginning of the twentieth century. The mixture was intended to protect the mahogany from attacks by *Hypsipyla robusta*. By the nineteen fifties there was profuse regeneration of the mahogany although whether this arose because of protection from borer attack or because mahogany is a shade tolerant and fast growing tree is not clear. A decision was made to manage the area as a selection forest favouring the more valuable mahogany (Tisseverasinghe and

Satchithananthan 1957). This has been done successfully for some thirty years now and the teak and jak had been reduced to about 20% of the crop by 1963 (Muttiah 1965). Felling is undertaken with great care and because of the value of the mahogany it is possible to insist on the contractors delimbing the trees before felling.

This is a rather unusual example of a nurse crop achieving its objective and then being retained as an equal partner in the upper canopy of the crop although much reduced from its original stocking. It also illustrates that there is the option to change the crop to be monospecific, though the circumstances at Sundapola are unusual in that selection felling techniques are being applied in essentially monospecific plantations in the tropics.

(c) West Africa

Expertise has been obtained in handling mixtures involving *Terminalia* spp., *Khaya* spp., *Heritiera utilis, Triplochiton scleroxylon, Nauclea diderrichii, Lovoa trichilioides* and *Aucoumea klaineana* among the indigenous species and teak, *Cedrela odorata, Gmelina arborea* and pines as exotics (FAO 1991b)

In the dense evergreen forests the establishment of *Heritiera utilis, Aucoumea klaineana, Nauclea diderrichii* (long rotation - greater than 35 years) and *Terminalia ivorensis, T. superba, Gmelina arborea* and pines (short rotation, 20 to 25 years) can be achieved in pure stands. Mixtures are needed for raising *Khaya ivorensis, K. senegalensis* and *K. anthotheca* with *Heritiera utilis* and *Nauclea diderrichii*; in which case there is the option to convert to the secondary species if the *Khaya* proves unsatisfactory.

In the transition zone from dense evergreen to dense semi-deciduous forests *Terminalia ivorensis* and *T. superba* can be established as mixtures or either of these two species can be mixed with *Triplochiton scleroxylon*; the proportion of the components can be controlled by early or late thinning. In the dense semi-deciduous forest zone these species and also *Gmelina arborea* can be raised with teak as a secondary species. But all these species together with *Cedrela odorata* can also be raised as pure crops.

In the tree savannas teak and *G.arborea* can be raised either pure or in mixture.

It is of interest that teak is considered to be a secondary, shade tolerant species, whereas elsewhere it is usually considered as a dominant, light demanding species. Of the above species the light demanders are *Terminalia* spp., *Triplochiton scleroxylon, Aucoumea klaineana, Gmelina arborea, Cedrela odorata* and the pines, while *Heritiera utilis, Khaya* spp., *Nauclea diderrichii* and teak are considered to be relatively shade tolerant.

According to experience, the mixtures to be avoided because of incompatible growth rates (Dupuy 1985) are:

Tieghemella spp with *Heritiera utilis*
Cedrela odorata with *Entandrophragma utile* or *Terminalia ivorensis*
Terminalia ivorensis with *Khaya* spp or *Entandrophragma utile*
Triplochiton scleroxylon with *Khaya* spp or *Tieghemella* spp.

In Mamu River Forest Reserve in Nigeria mahoganies (*Khaya* spp, *Entandrophragma* spp and *Lovoa trichilioides*) were raised in a matrix of *Gmelina arborea*, which was felled on a ten year coppice rotation. After two or three such rotations the mahoganies over-topped the *G. arborea* and formed a closed canopy, but it was doubtful if there was a positive economic return (Lowe 1991).

The essential lessons to be learned from the West African experience is that successful mixtures for wood production depend on the careful matching of species to site and a knowledge of which species are ecologically and silviculturally compatible.

(d) Eucalyptus clonal plantations.

At Aracruz in Brazil a pulp mill has been built which is served by 82,000 ha of eucalypt plantations. They are managed on a seven to eight year rotation and as a result of an intensive breeding programme are highly productive and each of the varieties used is very uniform. This has been achieved by developing clones with the required characteristics for vigour, straightness, branching, coppicing ability, disease resistance, wood density etc (Burley and Ikemori 1988; Aracruz Cellulose 1988; Campinhos and Ikemori 1986). Forestry plantations here approach about as close as they can to short term agricultural crops and are, one might think, about as far removed from the concept of mixed plantations as is possible, although it should be noted that there are different species and hybrids. Though there is always the temptation to concentrate effort on the very highest yielding clones, a decision was made to have a pool of about one hundred clones and furthermore to ensure that a selection from 15 to 20 clones should be used on each site type. The decision then had to be made whether to mix clones in one compartment or whether to achieve a mixture in the broad sense by juxtaposing compartments of different clones. The latter course was taken partly because unless the clones were equally competitive one would be suppressed with a certain loss in uniformity and a probable loss in yield, but also because an intimate mixture was considered to give no advantage in combatting pests and diseases and quite possibly might make attacks more likely. It has been speculated that a mixture of a few clones carries a higher risk of losses from pests and diseases than does either a mixture of many clones or a single clone (Libby 1982). With a monoclonal plantation unsatisfactory compartments could be harvested early and replaced with the minimum disruption to routine, while a mixed compartment of which one component was unsatisfactory would be difficult to treat.

In addition there is a policy at Aracruz of retaining 20% of the area, mostly along rivers, under indigenous forest and these have been enriched with fruit and other trees. The objective here is both soil protection and the encouragement of insectivorous birds which may help control insect attacks on the eucalyptus as well as conserving biological diversity.

Thus even in this very high yielding operation in which species diversity has been deliberately reduced, a policy decision has been made to forgo some short term gains in order to have a mixture of clones available and thereby to include an element of diversity. In the eucalypt plantations at Pointe Noire, Congo, the pool of clones is smaller and over half the area has been established with only 5 clones (Martin et al. 1989). The genetic base has recently been widened through the development of a concurrent programme of controlled crossing (Martin 1991). There has also been diversification into sawn timber production (Cossalter 1991). The means by which the risks involved in the use of clonal material may be reduced have been summarised by Matziris (1991) as the use of a large number of clones in mixture or mosaic, the rotation of clones over time and the regular introduction of new clones combined with sexual reproduction for the production of new clonal material and as a back up.

Conclusions on the management of mixtures.

Successful mixtures of two or more species on one site, to meet any one or more objectives, depend on management having clearly defined aims for establishing mixed plantations and then on selecting species that are compatible. A knowledge of the position of the species in the successional hierarchy in the ecosystem is helpful, but information is also needed on the silvicultural requirements of each species.

Mixtures involving the growth of one species under another, for example nurse crops or ground cover, are generally relatively easy to manage, though skill is still needed in removing an overstorey if the shade tolerant species is to form the final crop.

The management of mixtures of two dominants is much more difficult; they can usually only be managed on a narrow range of sites and often result in the suppression of one of the species and hence a reversion to an essentially monospecific stand. Although examples have been quoted where two or more species have been grown together on the same site, in general it is believed that the lack of trained and experienced staff in many tropical countries, combined with the lack of continuity of staff and financial guarantees make the successful management of dominant mixtures unlikely at the present time.

There is some justification for planting mixtures as an insurance against an unpredictable event, e.g. drought, frost, waterlogging, salinity, but the need to ensure that the species are broadly matched to the site still remains and there is a general tendency for these mixtures to become homogeneous by the end of the rotation. There is little evidence to indicate that mixtures are effective in preventing attacks by unspecified pests or diseases.

A strategy of broad sense mixtures, where a range of suitable species are available, and the enforcement of good forestry practice, will very often achieve the required stability. Some of the strategies now being advocated on ecological grounds in Germany, such as wider spacing in plantations, are very similar in effect to some of those adopted in southern Africa forty years earlier on economic grounds.

6. YIELDS.

The measurement of yields of wood (as opposed to other benefits) in long rotation tree crops is not easy. Longterm experiments need to be large, are difficult to control, have a high incidence of mishaps and in consequence a high coefficient of residual variation. For these reasons there has been a tendency to use mathematical modelling techniques to derive yields, but these measure yield potential under optimal or standardized conditions and the inputs to the models are often from undisturbed plots. The measurement of actual yields, however, reflects the real situation and the inputs then are derived from average plots exposed to average treatment and to the average occurrence of calamities. The emphasis in this case will be on large data input, the relevant grouping of stands and plots and the use of regression functions for describing the processes.

North America and temperate Asia.

Some attention has been given to the effect on yields of wood of an admixture of nitrogen-fixing species.

Alder (mostly *Alnus rubra*) in North America in mixture with conifers e.g. Douglas fir (*Pseudotsuga menziesii*) on nitrogen poor sites can result in a large increase in the conifer yields, though the increase may not be apparent until after about age 30 in the case of the conifer (Binkley 1984; Binkley & Greene 1983). The beneficial effects may only be apparent when the nitrogen fixing species is dominant or co-dominant in the stand and on nutrient-poor sites these species are unable to fix N_2. On nitrogen rich sites overall yields usually remain unaffected or may decrease, while the yield of the conifer component usually decreases (Binkley and Greene 1983).

Admixtures of alder, black locust (*Robinia pseudoacacia*) and in particular autumn olive (*Elaeagnus umbellata*) can have an effect on the growth of walnut (*Juglans nigra*) in North America; nitrogen mineralization is greatly increased and there may be a corresponding increase in the yield of the walnut which can be as high as 30 fold (Paschke *et al.* 1989; Schlesinger and Williams 1984). But there is also an instance of walnut basal area growth not being closely correlated with soil nitrogen concentration, even though nitrogen was being fixed satisfactorily in the topsoil by alder and other nitrogen fixing species (Friederich and Dawson 1984).

In mixtures of light demanding species one component tends to be suppressed by the other. Cherrybark oak (*Quercus falcata* var *pagodifolia*) will be suppressed up to the age of 25 years when grown in close association with sweetgum (*Liquidambar styraciflua*) or american sycamore (*Platanus occidentalis*). The more valuable cherrybark oak had better form when grown in close association with other species and after 25 years of age was able to compete with them (Clatterbuck et al. 1987; Clatterbuck and Hodges 1988).

The concept that one species can fill a niche in a stand without detriment to the main species is attractive. It is suggested that this may occur in rather special circumstances such as in Finland in spruce/birch mixtures where *Betula pubescens* grows in gaps in badly established spruce (Mielikainen 1985). But an example from North America shows that though the natural admixture of *Tsuga canadensis* into hardwood stands increased the standing volume on two sites by 30% & 20%, this in fact involved a 20%

reduction in the volume of the more valuable hardwoods, such as *Quercus rubra* (Kelty 1989).

In Japan a mixture of *akamatsu (Pinus densiflora)* and *hinoki (Chamaecyparis obtusa)* resulted in a greater overall volume, but a lower volume of *hinoki* (Kawahara and Yamamoto 1986).

Europe.

The admixture of beech (*Fagus sylvatica*) with spruce (*Picea abies*) is claimed to increase total yields by 15% (Schutz 1989). This is, however, less an example of an interaction between the species than a reflection of the fact that the spruce grows faster than the beech; pure spruce stands may be even more productive.

The interaction of *Picea abies* and *Pinus sylvestris* has been examined in some detail in Scandinavia (Jonsson 1961). A positive interaction, known as the "mixed species effect", has been identified when pine and spruce are mixed on sites where both species can be expected to do well. The benefits of this effect reduce as the site changes to favour one or other of the species - drier, less fertile sites favour pine; wetter, more fertile sites favour spruce. There is also a corresponding tendency for the favoured species to become dominant and to form monospecific stands, or at least a mosaic of monospecific groups. This tendency has also been noted with other species in Holland (Heybroek and Tol 1985). The mixed species effect varies with the parameter measured; for height it is positive for both species; for diameter growth, however, it is positive for pine, but of no effect or slightly negative for spruce (Jonsson 1961). More recent work on pine/spruce mixtures on *Calluna* heaths and peat has indicated a strong positive effect on the growth of *Picea sitchensis* (Malcolm *et al* 1990). The mixed species effect (or synergy) makes comparison between mixed and pure natural stands on different sites difficult, if the Site Index is defined by dominant height, since mixed stands will be tend to be compared with pure stands of a higher Site Index. This fact may have disguised the benefits of mixed stands (Jonsson 1961). Site Index has then to be defined by the less precise method of observing soil characteristics, vegetation types and indicator species.

The interaction of birch with conifers is more complex. This has been investigated in two studies in Finland and Sweden (Mielikainen 1985; Tham 1988) using yield modelling techniques. The general interpretation of the interactions of birches with conifers is similar in the two studies, but the yields and scale of benefits are much higher in Sweden; this may be an effect of site or only of the assumptions made in the models. *B. pendula*, a pioneer species that initially dominates the main crop may have a beneficial effect on spruce (*Picea abies*), which is a shade tolerant species, even when the birch is retained to full rotation. Pine (*Pinus sylvestris*) is a shade intolerant species and therefore though birch increases yields in open stands, in close competition birch depresses height growth of the pine. One solution is to cut the birch back for the first seven or eight years until the pine has a 1 m height advantage (Mielikainen 1985), but this would appear to reduce the value of the birch as a nurse crop. Birch should never be allowed to remain to full rotation in pine stands, because the total yield will be depressed. *B. pubescens* may have a depressing effect on conifers (Mielikainen 1985) and is less beneficial (Tham 1988).

Table 3 Spruce - Birch Yield estimates - Sweden

Age	Species	Pure #/ha	Pure Ht m	Pure Vol m^3/ha	Mixed #/ha	Mixed Ht m	Mixed Vol m^3/ha	
25	Spruce	1936	5.3	39	1936	5.5	23	
	Birch	-	-	-	600	15.8	78	thinned at age 25
50	Spruce	1237	14.6	300	1238	15.0	300	
	Total yield			300			378	

Source: Tham (1988)

Note: This assumes a light thinning of the spruce at age 30 & 40 years.

Thus by retaining the *B. pendula* an extra 78 m^3/ha is obtained and though this is at the expense of 40% of the spruce yield at age 25, that deficit is made up over the following 25 years to give an overall gain as much as 25% in a 50 year rotation. The gain in yield is dependent on the ability of the spruce to respond to release after being semi-suppressed, since shade intolerant species do not have this ability. If *B. pubescens* is used the gain is some 20 m^3 less, possibly because of the fast initial growth of this latter birch species.

Table 4 Spruce-Birch & Pine-Birch Yield estimates - Finland

	B. pendula Total	*B. pendula* Saw Timber		*B. pubescens* Total	*B. pubescens* Saw Timber
	------- Vol m^3 -------				
Spruce SI $24_{(100)}$	Rotation 90 years				
Spruce 100%	425	266		415	257
+ Birch 25%	438	282		394	217
+ Birch 50%	433	251		390	184
Pine SI $28_{(100)}$	Rotation 80 years				
Pine 100%	615	371			
B.pendula 100%	493	200			
Mixed 50%	625	350	birch thinned out age 40		

Source: Mielikäinen (1985)

Note: A 25% admixture of *B. pendula* in a stand of spruce increased total yields by 3% and saw timber by 6% in comparison to a pure spruce stand, but a 50% mixture resulted in a lower increase of either spruce or pine and a depression of saw timber production.

The evidence from Sweden and Finland suggests that a "mixed species" effect can be obtained with careful management, but interpretation and extrapolation of the results is not simple. In the first place, the birch arises from natural regeneration, rather than from planted stock, and secondly the effect is more important on the stocking of the site as a determinant of yield, than on yield at a given stocking. Despite the increase in wood production shown in experiments there are doubts whether, in practice, the advantages can be clearly established (Agestam 1991).

It is much more difficult to construct a yield model for a bispecific stand than for a monospecific stand; each additional species compounds the difficulties. A model has been developed for southern USA which assumes that individual components of mixtures behave very much the same as for pure stands (Nelson 1964); there is no indication that this model has been tested in the tropics and it is not known whether it would be valid there.

Tropics.

The outstanding example of the benefit of mixtures is the *Eucalyptus saligna/Albizia falcataria* experiments on the Hamakua coast of Hawaii on an abandoned sugar estate. In one experiment, which also included *Acacia melanoxylon* as one treatment, a 40:60 *Eucalyptus:Albizia* mixture resulted in a 140% increase in total yield of wood over the pure *Eucalyptus* at the age of 65 months. Even when only the *Eucalyptus* component of the mixture was considered that showed a 60% increase over the pure plot. A 50:50 mixture of *Acacia melanoxylon* and *Eucalyptus* gave a lesser response, but even that showed a 50% overall increase and only a slight drop in the yield of *Eucalyptus* in the mixture. The experiment received an application of fertilizer to all treatments. (DeBell *et al.* 1985).

In another experiment in which all treatments received fertilizer in the first year but only the *Eucalyptus* plot received further applications in each of the following three years, the admixture of 25% or less *Albizia falcataria* resulted in a drop in total yield at the age of 48 months, while if the proportion of *Albizia* was increased to 34% or higher then the total yield of the mixture was greater, but not significantly so, than the pure *Eucalyptus* plot. The yield of the *Eucalyptus* in the mixtures was consistently less than in the pure plot, but when the *Albizia* component exceeded 50% the *Eucalyptus* individual tree volumes were significantly greater than in the pure plot. There was no comparison with a plot of pure *Albizia*. As the comparison was being made with a heavily fertilized pure plot of *Eucalyptus* the results were biased against the mixture. It is assumed that a comparison with *Eucalyptus* receiving standard rates would have shown all the mixtures in a much more favourable light (DeBell *et al.* 1989).

Table 5: *E.saligna-Albizia falcataria* & *E.saligna-Acacia melanoxylon* mixture Hawaii.

Experiment 1 Mixture	65 months Stems per ha	Dry Wgt tonne/ha	Experiment 2 Mixture	48 months Stems per ha	Dry Wgt tonne/ha
Eucalypt	2200	37.6	Eucalypt	2396	93.7
Eucalypt	1012	35.3	Eucalypt	2101	58.1
Acacia 50%	1012	16.2	Albizia 11%	278	8.9
	2024	51.5		2379	67.0
Eucalypt	838	58.2	Eucalypt	1562	57.8
Albizia 60%	1225	37.1	Albizia 50%	833	44.8
	2063	95.3		2395	102.6
			Eucalypt	815	53.4
			Albizia 66%	1632	50.8
				2447	104.2
			Eucalypt (standard fertilizer)		44.0

Source: DeBell et al. (1985, 1989)

It is to be inferred from these figures that the beneficial effect of the nitrogen fixing *Albizia falcataria* (or *Acacia melanoxylon*) only takes effect when there is a sufficiently high proportion of the nitrogen fixing species. This effect was noted in North America (see chapter 3).

The experiment was conducted on an old sugar estate, where soil nitrogen is likely to have been depleted, but other nutrients may still have been in good supply. It should never be overlooked that on other sites in Hawaii this mixture has done poorly or has even failed.

In Espirito Santo, Brazil a mixture of *Eucalyptus urophylla* and *Leucaena leucocephala* resulted in higher mortality in the eucalypt and lower total yield at the age of seven years. It was thought that the mixture had promoted humid conditions which had favoured the spread of spores of *Cryphonectria cubensis* which attacked the eucalypt. The plots had received nitrogen fertilizer which may have prohibited the N-fixing effect of the *L.leucocephala* (Moraes de Jesus and Brouard 1989).

Measurements of yields of mixed plantations have been made in the hills of Nepal, not far from Kathmandu. Comparative measurements of pure and mixed stands were not made, but the differential response to site of the planted pines (*P. roxburgii*, *P. wallichiana* and *P. patula*) and broadleaved species dominated by *Schima wallichii*, which appear naturally in the pine plantations, was apparent. In a ten year old plantation the yield (stem plus leaf) of the pines varied from .8 to 6.7 tons/ha/year with the highest yields on old grazing sites which had few remnant broadleaved species, while the broadleaf species (with yields of 1.8 to 6.7 tons/ha/year) did best on old forest sites and on abandoned cultivation on terraces. On these latter sites the pines suffered from competition with the broadleaved species (Mohns et al. 1988).

Conclusions on yields.

There are some examples in both temperate and tropical zones of higher total yields of wood volume of mixtures as compared to pure plantations. But accurate species/site matching and the choice of complementary species is critical to success and the effect of one species on another can change with site and in time; gains are also dependent on the timing and scale of forest management interventions. Furthermore the total gains may be small and in industrial plantations may not be on the most valuable component of the mixture.

The construction of polyspecific yield models of tropical rainforest species in plantations, given the potential number of species and the lack of data, is difficult. But just because it may prove impossible to predict the development of mixtures in the tropics with any precision, it does not follow that such mixtures should not be tried.

The number of examples of yield records in the tropics are limited and where mixtures have not resulted in gains, it often appears that there has been a lack of clarity in defining the objective of the mix and therefore a possibility that the species are inappropriate. The outstanding example from Hawaii quoted above must be treated with caution as a general model because of the confounding factors applying there.

Yield of wood is a good measure of success of industrial plantations and for fuelwood and pole plantations, but it is inappropriate where plantations have been established for environmental reasons - to control erosion, enhance soil fertility, ameliorate the microclimate or to provide direct social benefits. The evaluation of these "non-market" benefits are discussed in more detail in the next chapter.

7. ECONOMICS.

Economics concerns the commitment of resources to production and the return in yields of value to society. Plantation forestry in tropical countries may be favoured by the availability of land with low opportunity cost and the availability of labour at low wage costs. Technological know-how and managerial skills, however, may be more scarce and therefore more costly. The physical environment may be favourable to rapid, high volume growth of favoured species. This has a commensurate cost in that weed growth is also heavy and therefore expensive to control. The local market value of the product may be relatively low because of low demand from the low income economy due to the availability of low-cost alternative wood material from natural forest or because of the distance and cost of transportation involved in reaching alternative markets. The equation alters as the local economy develops, changing both the supply cost of inputs and the demand for products.

An investment in tree planting matures over several years and it is most important in assessing such an investment to take account of the displacement in time between the expenditure and the income. In the case of many tropical tree crops this displacement may be relatively short compared with equivalent periods in temperate countries - 10 to 20 years compared with 50 to 100 years for example, to produce final yields of 200 to 400 m^3/ha.

The concept of Net Present Value provides a useful tool for evaluating on a comparable basis expenditure and income occurring at different times in the production cycle and thereby allowing the comparison of the "profitability" of different crops and different options within crops. In such assessments the assumption is made that all costs and benefits can be expressed in monetary terms and that a discount rate can be selected which relates all values occurring at different times to present day values.

In industrial plantations, where revenue from sales is the prime benefit and the inputs are bought and sold in established markets, a financial analysis is straightforward. Thus a positive financial return may be expected from a high-yielding species in favourable and constant growing conditions with established markets, as with plantations of eucalypts at Aracruz in Brazil or at Pointe Noire in Congo. On the other hand, cost/benefit analysis of the United Kingdom Forestry Commission plantations, considering only "market" benefits gave a negative financial return. Including "non-market" values and environmental benefits, such as amenity, recreation, preservation of the landscape and the function of plantations as carbon sinks indicated a positive economic return (Bateman 1991). When the main objective of a plantation is to rehabilitate degraded sites, the protection of watersheds or soil conservation, then the correct pricing of environmental benefits becomes even more important although the criteria for assessing environmental benefits are not well developed. It is to be noted, however, that the necessity for pricing environmental benefits is becoming generally accepted. An analysis of rates of return of World Bank forestry projects showed 15-21% for 8 Watershed Rehabilitation projects, 15-30% for 27 Agroforestry/Fuelwood/Community/Social projects, but only 10-15% for 15 Industrial plantation projects (Spears 1985). However, it is not clear to what extent "non-market" values have been included in the economic analysis of any plantation projects.

Scarcity of investment resources leads financial authorities to adopt high discount rates which favour high yielding species, short rotations and management policies of minimum cost and high output, which in the absence of adequate trials and experience may also tend to involve high risk. Such a policy will oblige managers to employ quick acting, often expensive solutions to problems such as the addition of artificial fertilizers to relieve unforeseen nutrient problems, the use of chemicals and aerial spraying to overcome outbreaks of disease and pests. Where benefits are perceived from the establishment of mixed plantations, on the other hand, they may be achieved at the expense of lower yield. This "low input/low output/low risk" approach is likely to be of value in long rotation crops, but would be ruled out by high compound interest rates over long periods. Some authors have questioned whether high discount rates are appropriate for the analysis of long term projects and have also suggested that the long term "real" interest rates in industrial countries are only in the order of 2-4% (Leslie 1987).

Be that as it may, it is clearly imprudent to enter into an investment in plantations without ensuring that the expected returns will be sufficient to repay the costs and liabilities involved in the project. Society, through the Government or the community, may be willing to increase funding in order to pay to secure benefits from which there is no direct cash return to the investor, but which are perceived to be of value to the community - soil and water conservation, amenity and other environmental benefits are examples. Clear identification of these benefits in the objectives of a plantation project is essential to a sound economic evaluation.

The economics of mixtures.

Mixtures may have advantages of symbiosis, although the evidence presented in Chapter 6 on the effects on yield of wood is not conclusive. They may have advantages of spreading the income-generating period through the removal and sale of the products of one of the species early in the rotation. Species may be mixed as an insurance against the risk that one or another will be attacked by pests or disease. On the ground that the trees remaining will have gained from the intermixture during formative years the loss from pests or disease may be less than proportional to the deaths since the dying ones may also be harvested. Finally, there may be an amenity, aesthetic or ecological preference for mixture.

The economics of each of these types of scheme may be analyzed through the present value assessment discussed above, through appropriate estimation of costs and revenue and evaluation of non-market benefits.

Temperate experience.

In Scandinavia thought has been given to the theory of mixed plantation economics, but is mainly centred on the management of naturally occurring broadleaved species in planted conifer stands. Because harvesting is so long after establishment and prices for the final product are unpredictable, the argument has been proposed that:

- the initial investment should provide a choice (i.e. should be a mixture), not least because there is a strong possibility that over a long rotation objectives may be redefined;

- thinning and a final choice between the two components for the final crop should be delayed as long as possible.

This gives the best opportunity to identify the species that will have the greatest chance of commanding the higher value at final felling and providing that both species are equally suited to the site, at no extra risk of the biological failure of one of the species. This principle has, of course, to be constrained within silvicultural and management limits; for example, overstocking may lead to stagnation, or late thinnings may cause excessive damage to residuals. It is also confined to market values rather than to the values of other benefits, nor does it take into account the effect on the soil over several generations. Within these limitations, the theory assumes that relative price changes are essentially random, but are related to previous prices in inverse proportion to the time elapsed. In other words predictions of prices are likely to be more accurate over a short time span than over a long one. It has been suggested that economic gains from mixed stands, which may in addition include early returns from more valuable thinnings, have been underestimated and are in all probability much larger than the much-discussed, but often small and doubtful mixed species effect (Lohmander 1990). It should be noted that in Scandinavia the secondary species, which are mostly birch and aspen, and also the regeneration of conifers, occur naturally in plantations. The broadleaved species have until comparatively recently been treated as weeds; it is only since a market for birch has re-developed that it has contributed to income.

The argument is sometimes made that the inclusion of a secondary species can improve the quality and hence the profitability of the main species. Examples include:

- suppression of epicormics on red oak and the maintenance of a ground cover suitable for oak regeneration by the hemlock understorey (Kelty 1989);

- increased bole length in cherrybark oak in competition with *Liquidambar* (Clatterbuck and Hodges 1988);

- suppression of spruce side branches by *B. pendula* resulting in a 6% gain in saw timber yields (Mielikainen 1985). But though the admixture of 25% *B. pendula* resulted in a small gain in total yield of pines it apparently depressed saw timber yields by 5% - see Table 4;

- other studies show that retention of birch increased the height of self-pruning on pine and reduced the knotty core; any extra tending costs paid were covered by returns. These were, however, effects of density rather than of species mixture and could - though at extra cost - probably have been achieved by closer spacing of pines (Haegg 1988, 1989, 1990).

It is not known how large these benefits will be.

Tropical experience.

No economic analysis of mixed plantations in the tropics was noted in this study. In the accounts of the *Eucalyptus/Albizia* experiments in Hawaii there was no mention of the economics of growing the mixture. The trees were being raised for an energy project, therefore the prime objective must have been to grow as much biomass as possible. Although the lighter *A. falcataria* wood would be more expensive to handle because of the larger number of stems and because it is branchy it would be more liable to felling damage, its value as biomass would be nearly as high as that of the eucalypt. In an energy plantation the mixture, given the results quoted, can be expected to be an economic success. But if the objective had been to grow the eucalyptus for saw timber, the economic advantages of the mixture would not have been so obvious; the value of the two timbers in relation to end use is important.

In Nigeria, as mentioned earlier, *Nauclea diderrichii* (opepe) is used as a nurse crop for members of the Meliaceae family - *Entandrophragma, Khaya, Lovoa* - thereby reducing the incidence of *Hypsipyla robusta* and giving an intermediate yield from the sale of the poles of the Opepe. It was found that the Internal Rate of Return for Opepe grown on a timber rotation of 60 years was 4.5% whereas when it was mixed 5 Opepe to 1 *Meliaceae* the IRR increased slightly, to 4.6% over the same rotation (Ball 1979). The reason for the small difference between the two rates was the lower final volume of the *Meliaceae* compared to pure Opepe, despite the higher value of the *Meliaceae*. It was also found that the high demand for the Opepe poles led to felling of the best-formed in the early thinnings, leaving the poorest for the final crop, and causing severe damage to the final crop trees in the process.

The mixed plantations of *Swietenia/Securinega* being tried in the Solomon Islands also have this potential. But in this and other cases, the extra income is only possible if there is a market for thinnings. In the nineteen fifties there was no local market for nine year old thinnings in Nigeria (Henry 1960) whereas the rapid extension of the electricity supply in the nineteen seventies led to a high but unforeseen demand for Opepe poles. In India the use of *Gmelina arborea* as a nurse for *Dipterocarpus turbinatus* worked well silviculturally, but the nurse crop had to be removed before it was saleable and there were problems in controlling the coppice regrowth (Indian Forest Service 1939).

In Scandinavia it has been shown (above) that the retention of naturally occurring mixtures can be economically advantageous. A comparable situation in the tropics - invasion of a plantation by pioneer species such as *Macaranga* spp., *Anthocephalus chinensis, Neoboutonea macrocalyx* or *Croton* spp. can easily be envisaged. But the interaction with the main species, particularly if that is an exotic conifer, may not be so benign as in Scandinavia and markets for the secondary species have not been widely developed.

Long term gains and losses.

The benefits of mixed planting to soil improvement and the maintenance of site conditions over several rotations are of the utmost importance. These are benefits that are difficult to quantify or, since the time scale is so long, to accommodate in an economic model. The situation can arise in which a crop can deplete a site of one nutrient without necessarily reaching a condition of deficiency in the first few rotations. The yields of that crop would be considered sustainable, if no account were taken of the loss of nutrients and the risk of a sudden decline in yield when the threshold for that nutrient is crossed. In the long run what is needed is sustained fertility as well as sustained yields. To achieve this it will be necessary to incur costs or to forgo short term financial benefits. The short term (one or two rotations) economic models usually applied should not be used to blind foresters to the risks of long term site deterioration, which can possibly be ameliorated by the use of mixtures.

Risk evaluation.

Economic analysis should include some evaluation of the risk of failure attached to any enterprise. Those who advocate mixed plantations are often motivated by the desire to reduce the risk of a major failure from some unpredictable catastrophe, such as insect or fungal attack or drought etc. The concept of mixtures as an insurance, discussed in Chapters 3 and 6, is a recognition of this risk. However, this insurance may entail a cost in reduced yields and higher establishment and management costs. In New Zealand, where 85% of the plantations are planted to *Pinus radiata*, the argument has been proposed (Burdon 1982) that a policy of investing in one species is justified on the following grounds:

- that *P.radiata* has been well matched to the sites available in New Zealand and there is no particular reason to anticipate catastrophic epidemics,

- that should a serious disease or pest arise, such as *Dothistroma pini*, New Zealand has the financial and staff resources to combat it,

- that there is no evidence that *P.radiata* is any more susceptible to pests or diseases than native naturally regenerated stands, such as, for example, insect (*Platypus*) attacks on *Nothofagus*,

- that within this one species an investment has been made in maintaining as broad a genetic base as possible, which reduces the chances of catastrophic epidemics such as have occurred in poplars,

- that silvicultural management includes early and heavy thinnings and rotations are short, so that in the event of an epidemic harvesting can be brought forward at a minimum loss and the affected site can be re-established to another provenance or species. In the past epidemics, e.g. *Sirex* wood wasp, have been the consequence of lack of silvicultural management, and

- that research into other species potentially suitable to New Zealand conditions is being carried out and tested alternative species could be introduced into the plantation programme at short notice if required.

In short, New Zealand having selected a species for wood production and watershed protection that is well matched to the available sites and having made a careful analysis of the risks, has decided that it is more advantageous to continue to invest in a proven highly profitable species rather than to reduce profits by investing in a range of lower yielding species.

The risk analysis that has been undertaken at Aracruz, Brazil has arrived at a similar answer. The objective is high yields over a short rotation. On the one hand the risks attached to reduced species and within-species diversity in the production populations are considered to be small and there is a good capability for handling any "catastrophe". On the other hand the convenience of management and the gain in yields of monoclonal plantations are highly attractive. Provided precautions such as maintaining a large genetic base in parallel base populations are taken, a reduction in species and within-species diversity can be justified.

Many developing countries wish to invest in industrial plantations but have neither the resources for research to counter epidemics nor the knowledge of a species that the foresters of New Zealand have of *P.radiata* or that Aracruz Cellulose has of *Eucalyptus* spp. For developing countries a policy of spreading the risk by having a mixture of species in industrial short rotation plantations in the broad sense, in which the species are carefully matched to the sites available, may be desirable. Where long rotation crops are proposed the policies of reducing the risk by careful species/site matching and of spreading the risk by using more than one species are of as much (if not more) importance as with short rotation crops, and there may be opportunities for intimate mixtures if circumstances permit - that is, if there is sufficient knowledge of the silviculture of the species proposed for the mixture, the objectives can be met or other benefits can be identified. Where the objective is watershed management or rehabilitation of degraded lands then mixtures, especially in the sense of encouraging an understorey, are often the most appropriate composition.

Conclusions on economics.

Little fully evaluated information on the economics of growing mixtures in temperate regions or in the tropics was found in this study. Theory suggests that establishing mixed plantations makes it possible to keep options open as long as possible in order to obtain the best prices or range of products. If mixtures, such as birch/spruce in Scandinavia, can be obtained at little cost it is possible that the economic gains can be added to any synergies in yields that there may be, but there are indications that the expenses of establishing and maintaining mixed industrial plantations in the tropics are often high. There are, however, circumstances where non-market benefits associated with amenity or ecology are regarded as important (see below).

The profitability and overall desireability of a mixture may depend on the ability to harvest one component of a mixture early in the rotation as in the case of *Nauclea diderichii* in mixture with *Meliaceae* in Nigeria. The increasing local markets for small wood or other products (such as rattan) will favour thinnings and in doing so will make the management of mixed species crops easier because there will be a wider range of species that can be considered for mixtures. The more species there are that have a commercial value the more economically attractive mixtures become, though the silvicultural requirements for releasing the main crop do not always coincide with the best moment for marketing thinnings.

The economic and biological success of mixed plantations will depend on the availability of adequate financial resources and of skilled staff as well as species suited to the sites, compatible with the other components and matched to the end uses available.

The above has considered only the effect on returns arising from mixtures in the provision of wood products. Species may be included in mixtures for other values - for instance, for the provision of fodder, fruit or nuts, or for the soil-improving properties of their leaves or associated nitrogen-fixing bacteria, or for their visual appearance. These are all valid reasons for planting mixtures, but they are difficult to evaluate because their products are not usually traded in markets.

8. MAIN CONCLUSIONS.

Plantations in the tropics and sub-tropics.

Plantations can supplement, but never fully substitute for, the range of goods and services provided from natural forests. Criticisms are frequently made of plantations on the grounds that they lead to impoverished ecosystems and a decrease in the number of plant and wildlife species. Although plantations could be established for the specific purpose of conserving genetic resources of one or a few specified tree species, and although the reconstruction of ecosystems has been attempted on a limited scale, most plantations are not established for such purposes and (unless they have replaced natural forest on the same site) their benefits should not be evaluated directly against the natural forest. It is also important to stress that the establishment of production plantations, which frequently implies the use of fast-growing, pioneer species, must not preclude research and development of a range of other, local, species; and that if an ecosystem is changed through the establishment of forest plantations (or agricultural crops) then care must be taken to conserve elsewhere representative examples of the local flora and fauna.

Forestry plantations in the tropics and sub-tropics make a greater contribution to people's needs for forest products than their relatively small area suggests, not just to the supply of industrial roundwood but also through the provision of many other goods and environmental services. The area of forestry plantations is likely to increase considerably, particularly when established outside the government sector by communities and individuals; the use of tree plantations to sequester carbon to reduce the accumulation of carbon dioxide in the atmosphere is also attracting much attention. The effect of species composition on sustaining the flow of benefits from these plantations is of considerable importance.

Mixtures of species in forest plantations may be deliberately created, or they may develop naturally through the natural regeneration of other woody tree species in otherwise single species plantations. Mixtures cover a wide range of options, from simple even-aged mixtures of two species to several species in a plantation managed as a selection forest. Mixtures are also taken to mean the planting of different species in adjacent blocks. Most plantations are at present planted with a single species, but objections to this on the grounds that it is environmentally unsound overlook the many single species associations that occur naturally. In fact, the fast-growing species best adapted to producing wood products on short rotations are frequently those typical of early stages in the forest succession in which there are few species; they may thus not be naturally adapted to growth in mixtures.

Decline in yields of wood

The evidence for a decline in yields of wood from single species plantations in the second or subsequent rotations appears to be based more on a failure to match species to site than to be due to the pure plantation itself. Nevertheless, nutrients will be lost from plantations due to harvesting,in particular those grown on short rotations. Permanent Sample Plots will be an important tool in detecting yield decline, but meanwhile foresters should avoid silvicultural practices likely to lead to losses of soil or organic matter. Silvicultural practice must also contribute to the recycling of nutrients through rapid litter breakdown.

Importance of site and objectives.

Species must be matched to the site; problems will arise where trees are planted off-site, There will, however, usually be a range of species that are silviculturally suited to any one site; the choice is then determined by the objectives of management. When objectives can be achieved through extensive management practices, as in the case of watershed management, rehabilitation of degraded sites, amenity planting and sometimes the production of fodder for livestock, it will often be beneficial to use species which, biologically, are able to grow in mixed stands and which can complement each other in the provision of a range of goods and environmental services. If, on the other hand, the objective is high yields of a uniform product, for example for a specific industrial process, then it is likely that monospecific, short rotation, intensively managed pioneer species will best satisfy the objectives of management.

In all plantation projects, however, there will be other objectives and constraints to the achievement of the main objects of management; such constraints should include the production of sustainable yields and the maintenance of site fertility. These secondary objectives or constraints to ensure environmental sustainability may lead policies away from single species plantations; for instance, to the creation of mixtures in the broad sense through grouping of monospecific plantations, or by rotating crops of different species, or by undertaking heavy thinnings to encourage the development of an understorey of shrubs and herbs.

Risk.

A mixture of species often provides an insurance against the risk of a total loss as a result of some catastrophic event or a change in markets or demand. The use of mixtures for the purpose of reducing overall risk in intensively managed plantations usually implies a reduction in profits because of the partial substitution of a valuable species by a less valuable one or because of greater management costs. Monospecific and, even more so, monoclonal plantations are usually associated with a "high input/high output" policy which is also often high risk. The justification for such a policy depends to a large extent on the ability of the manager (government, community, individual or company) to evaluate the risk, to allocate resources to overcome potential problems and to undertake research to anticipate problems. It depends too on the length of the rotation. Successful monospecific plantation projects are found in many countries, for example New Zealand, South Africa, some of the Australian states, Brazil, Chile and Congo, but where an organization cannot guarantee continuing resources some risk-spreading is advisable, even if only in the use of mixtures in the broad sense.

Although mixtures have usually been seen as an insurance against risk, examples have been quoted where species diversity has proved ineffective in controlling a disease, for example Chestnut blight in USA or *Dothistroma* blight in *P.radiata* in East Africa. It has been argued that mixtures can even increase risk from disease by providing an alternate host. There is little knowledge of the mechanisms by which pests and diseases spread and are controlled in a forest ecosystem; the chances that unproven, indiscriminate mixtures will control pests or diseases are small.

Monitoring growth, yields and soil fertility is important, but the monitoring of fertility is difficult and yield trends may be masked by advances in tree breeding and in silvicultural techniques and may not be detected until the next rotation. The need for action to sustain soil fertility through sound management practices has already been noted, and the use of mixtures may contribute to this aim.

Synergy.

There are some documented instances of mixtures enhancing not only total yield but also the yield of specific, valuable components of a crop. In Scandinavia this "mixed species" effect may be small, but there are indications that the use of nitrogen fixing co-dominant species could result in increases in yield. Such synergies are worth pursuing, but the sites on which they are achievable are limited and the conditions under which they operate have not been well researched in the tropics.

Types of plantations

(a) Industrial Plantations

Reduction of diversity in the production population is an object of management in order to maximize growth on valuable species and to obtain uniformity for industrial processes. Some natural ecosystems consist of a single or a few species, but in a single species plantation there is an increased risk of instability, although monospecific plantations may be easier to treat than polyspecific plantations in the event of attacks by pests or diseases.

The efficacy of mixtures to control attacks of pests and diseases is variable and uncertain. The mechanisms involved are often complex and the degree of mixing required may make it uneconomic to grow a vulnerable species. It is recognized that some valuable tropical timbers, notably some mahoganies, can only be established satisfactorily in shade which helps control attacks by *Hypsipyla*. Usually shade is best provided by another species and mixed mahogany plantations have proved silviculturally successful in many parts of the tropics.

The skills required to manage mixed plantations, particularly mixtures of dominants and co-dominants, are greater than for managing monospecific plantations. Badly timed interventions or incompatibility of the species used may result in malformation of stems or possibly a natural reversion to a monospecific condition.

Since the products of the final felling of industrial plantations in the tropics are often intended for the export market, mixtures may be economically more viable if a nurse or "in-filler" crop can be harvested early in the rotation. But this is dependent on there being a market for small size or non-wood produce from the nurse crop.

Second rotation decline is a real risk on infertile sites and cannot be discounted on fertile sites. It is controllable by good forestry practice which may include temporary or permanent mixtures of species to improve the decomposition of litter and thereby promote the recycling of nutrients and increasing the organic content of the topsoil.

(b) Less intensively managed plantations.

In fuelwood and pole plantations there is usually less need for uniformity of product and there is often greater scope for unmechanized harvesting and extraction. Therefore the factors that militate against mixtures in industrial plantations are less pressing and the opportunity to include mixtures to reduce risks or to favour soil improvement can be taken.

Fodder plantations should generally be mixed to give a succession of leaf forage throughout the year, particularly in the dry season. Windbreaks should also generally be of several species, to provide shelter at different levels and of different densities.

The growing of other woody species in association with the main species may offer economic advantages; two examples that are quoted are of rattans and of sandalwood.

(c) Plantations for site improvement.

Plantations established with the objective of site improvement - watershed management, rehabilitation of degraded soils and amenity can frequently be established as mixtures. The sites often present special problems about which little is known and a mixture represents an insurance against failure, though natural succession may anyway tend towards a limited diversity. A knowledge of the natural ecological succession of the site is helpful.

Conservation of wildlife

Most large plantations will have one main objective (such as wood production), with other subsidiary objectives or perhaps constraints to the main objective (such as soil conservation, catchment protection or the provision of direct social benefits). There may often also be objectives of wildlife conservation.

The maintenance of suitable habitats for the conservation of genetic resources and the production of wildlife species of commercial or subsistence value are the main objectives of wildlife conservation within forestry plantations. The contribution of forestry plantations to those aims can be greatly enhanced by adequate pre-planting planning and design, as well as by the actual day-to-day management of the plantation. Plantation schemes should be seen within the wider land use context, and within the scheme buffer plantings, corridors, the retention of islands of natural forest within the plantations and incentives to local people can all contribute to wildlife conservation.

The more the management of a plantation encourages overall plant diversity and the closer the plantation resembles the natural forest the greater will be the contribution to wildlife conservation. Mixtures of age classes and of appropriate species, along with the retention of some natural forest, will generally promote this conservation. Generalist large herbivores can reach high density where there is structural diversity in the plantation or even in young plantations or on clear felled sites.

9. RECOMMENDATIONS.

An exhaustive review of the literature comparing the advantages and disadvantages of mixed or pure plantations has been made. While there are many references concerned with the subject few of them record direct comparisons of plantations composed of a single species with those composed of more than one. This section makes some recommendations for practising foresters, forest research workers and planners concerned with forestry plantation development in the tropics and sub-tropics based upon the evidence that is available as well as upon those gaps in knowledge of the behaviour of species in pure and mixed associations.

The objectives of plantations.

It is recommended that plantations are established with specific objectives in mind in order to be able to evaluate their costs and benefits fully. It is only under these conditions that the choice can be made between single or multiple species composition.

Matching species and management practices to the site.

One of the principal recommendations arising from this study is of the importance of matching not only species and provenances but also management practices to the site to ensure that growth and yield of desired products are sustained in the long term. This recommendation will acquire added weight as plantations are extended in the tropics and sub-tropics onto sites that are marginal for the growth of the traditional plantation species.

Plantation guidelines, formulated at national and sub-national level and given the status of forest regulations are recommended in order to implement good forestry practice in plantation development. Such guidelines have been produced, for example, in Queensland (Kanowski and Savill 1990) and by the International Tropical Timber Organization in collaboration with FAO. Guidelines drawing attention to "best practice" in the planning, establishment and management of plantations have also been prepared by other organizations.

Situations where mixtures are appropriate

There are certain situations where it is recommended that the forest manager or planner should consider the use of mixtures of one sort or another in a forest plantation. These include, but are not limited to, the following:

- community forests, where more than one species in the mixture helps to meet multiple end-uses and acts as an insurance against failure of a single species;

- firebreaks in pure plantations, either in lines to create a discontinuity or in intimate mixture to introduce less flammable fuel;

- nurse crops, especially for reduction of insect attack as in the mixture of *Nauclea diderichii* with *Meliaceae* to reduce the incidence of *Hypsipila*;

- areas in which wildlife conservation is a stated objective, as distinct from action to minimise the impact of plantations on wildlife, through the creation of mixed plantations to establish a suitable habitat for wildlife.

Also, although different from a mixture of tree species:

- encouragement of a shrub and herb layer, through regular thinning and avoidance of overstocking; in fact, the good forestry practice recommended above;

- clonal forestry, where there should be a mixture of blocks of clones in the annual plantation area and the regular introduction of new clones arising from a continuing breeding programme of sexual reproduction (including hybridisation).

Growth monitoring.

There is little information in the tropics on the growth of pure stands on a full range of sites; the information on mixed stands is negligible. It is recommended that a network of Permanent Sample Plots in forest plantations should be established by countries with significant forest plantation programmes (including community tree planting). These plots should be maintained over several rotations, and are required in all major species; they must be established on a full range of potential planting sites. The Permanent Sample Plots should be backed by other growth studies including plots on which not only will the same species be re-established in successive rotations, but in addition the tree seed will be obtained from the same seed source as that of the original plantation, to minimise experimental error. The short rotations on which many species are managed in the tropics make this practicable. The plots will also be useful for deriving yield models.

Research.

There is an almost complete lack of experimental evidence on the benefits and constraints to the establishment, growth and marketing of forest plantations consisting of mixtures or single species in the tropics and sub-tropics. It is recommended that national, regional and international research institutions include such investigations in their programmes of plantation research. Some examples are given below:

- effect on long-term soil fertility and yield, especially the potential of nitrogen-fixing species to increase yields in mixtures and the effect of harvesting on soil nutrient status and the yield of subsequent rotations;

- identification of new species and provenances of trees and shrubs for use in mixtures, related not just to their yields of wood but also to their non-wood products and other benefits. Research may be needed to develop markets for the products of lesser-known species;

- compatibility of different species, whether trees or shrubs, when grown in mixture, particularly the existence of synergy between species and methods of management of mixtures;

- the potential of mixtures for forest protection, whether from insects, disease or fire, and particularly the mechanisms by which diseases and insect pests spread in forest ecosystems and the processes by which they are controlled naturally.

Economic analysis.

While data on the economics of plantations in the tropics in general is scarce, there is virtually no information on the economics of mixed plantations. It is possible that cost and revenue data are available, but there is no evidence that such figures have been collated and analyzed. It is recommended that data on the costs and benefits of plantation programmes are collected in such a way that would allow reliable comparison between mixed and pure plantations, especially over several rotations. Such data should attempt to quantify other benefits arising from the plantations in addition to wood products.

Most of the emphasis in this study has been on the biological effects of mixed and pure plantations but there may be important social or cultural reasons for the inclusion of species other than those traditionally planted for wood products in plantations. It is recommended that consideration is given to these factors when evaluating the options for the species composition of plantations.

APPENDIX 1

ANNOTATED BIBLIOGRAPHY

These references are far from comprehensive; the spread of subjects which touch on mixed planting is very wide. The notes only refer to aspects of the publication that appear to be of relevance to mixed planting.

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The tropics: Management. Soils
Net primary production in a rain forest may be used for maintaining a dynamic equilibrium. Nitrogen fixers may be particularly important in these forests. High temperatures and intensive rainfalls increase leaching in the tropics. Fertilization is costly and may cause leaching and may damage nitrogenous bacteria and mycorrhizae.

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General: Management, Research
A manual for designing and setting out Permanent Sample Plots.

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Monocultures are warned against. Mixing with broadleaved species is recommended to avoid the hazards.

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India: Soils
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Germany: Management

Pine/Spruce and Pine/Beech mixtures are less prone to Nun moth *(Liparis monarcha)* attacks. Pine/Beech and Larch/Beech mixtures have better soil structure. Oak/Beech mixtures in Spessart depend on early felling of beech for glassworks, allowing oak to come through.

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UK: Soils
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UK: Soils
26-year-old mixture of Spruce, Alder and Scots pine at Gisburn. Earthworm numbers and weight, soil NO_3, P status and tree height were increased by an admixture of alder and more so of pine. Admixed trees are assumed to have encouraged earthworms, resulting in an increased mineralisation of N and P.

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Germany: Management. Yield
The rigidity of present-day forestry is criticized. Guidelines for a more flexible and functional forestry are given. A practical example of implementation of these is provided.

Bruenig, E.F. 1991(a). ITTO guidelines for the sustainable management of man-made tropical forests (First Draft). Presented to the Permanent committee on reforestation and Forest Management at the seventh session, Quito, Ecuador.
Tropics: Management
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Global: Management
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Budowski, G. 1983. Biological diversity and forestation in the tropics. In: Strategies and Designs for Afforestation and Tree Planting. Proceedings of an International Symposium (Wiersum, K.F. ed.), PUDOC, Wageningen, 1984.
The tropics: Management
Advantages of plantations over natural forests are summarized. The so far limited, and largely disappointing, experiences of mixed plantations is discussed. An exception is the use of cover and shade crops.

Bule, L. and Daruhi, G. 1990. Status of Sandalwood resources in Vanuatu. In Proceedings of the Symposium on Sandalwood in the Pacific, April 1990, Honolulu, Hawaii. US Department of Agriculture, Forest Service, General Technical Report PSW-122. pp 79-84.
Vanuatu: Management.
A history of exploitation of Sandalwood in Vanuatu and an account of current problems and research.

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New Zealand: Environmental. Soils
Criticism of pure even aged plantations are summarized and discussed. It is concluded that pure even aged stands are not automatically more vulnerable than mixed stands. The limited success of exotics other than Radiata pine in New Zealand is noted.

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UK: Soils
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Global: Management
Statistics on forest fires and means of hazard reduction.

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Brazil: Management
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Campinhos, E. and Claudio-da-Silva, E. 1990. Development of the Eucalyptus tree of the future. Paper presented to ESPRA Spring conference, Seville, Spain. Aracruz Florestal S.A. mimeographed report.
Brazil: Management
Importance of breeding for pulp quality. Volume mai (1990) has fallen to 35m3 as against 45m3 in 1985 as a result of drought.

Canizares, E.G. et al. (1987?). *Propuesta de planificacion territorial de la actividad forestal en la Sierra del Rosario, Cuba*. IESACC, A.P. 8010, C. Habana 10800.
Cuba: Management
Derives a stress index for sites, and an index for each species' ability to cope with the stress. Using these indices, it should be possible to match species to sites.

Carlson, A. 1986. A comparison of birds inhabiting pine plantation and indigenous forest patches in a tropical mountain area. Biological Conservation 35: 195-204.
Kenya: Wildlife

Specialist species were more impoverished in Radiata pine plantations than were generalists. Palaearctic species were favoured by pine. Native forests reserves are needed, and islands and mosaics of native plant species.

Carlson, P.J. and Dawson J.O. 1984. Effects of autumn-olive and black alder leaf mulches on the growth of eastern cotton wood in two soils. Forestry Research Report, Dept. of Forestry, Agricultural Experiment Station, University of Illinois 84-1: pp 3.
USA: Soils
In pot experiments, mulch of *Alnus glutinosa* and *Elaeagnus umbellata* leaves (especially of the latter) improved growth of *Populus deltoides* in both loamy prairie soil and 2:1:1 sand:peat:soil mixture. N-fixing species may be beneficial even on fertile prairie soil.

Cellier, K.M., Boardman, R., Boomsma, D.B. and Zed, P.G. 1985. Response of *Pinus radiata* D.Don to various silvicultural treatments on adjacent first- and second-rotation sites near Tantanoola, south Australia. I. Establishment and growth up to age 7 years. Australian Forestry Research 15: 431-447.
Australia: Management, Soils
Description of treatments on paired first- and second-rotation plots. Of particular effect were weed control using a herbicide, Phosphate addition at high level and Nitrogen at moderate level; lime effective on 2nd rotation. No difference between yields of two rotations at optimum levels; overall increase in yield of 30%.

Chaffey, D.R. 1978. Decline in productivity under successive rotations of forest monoculture. Land Resources Division, Miscellaneous Report 243, ODA, London.
General review
Literature review under the following main headings; pathogens, soil - physical properties, soil - chemical properties, biological factors and climate.

Champion, H.G. 1954. Forestry. Oxford University Press (UK).
General textbook: Management
Line and matrix mixing are briefly explained. The relative rarity of successful mixtures is noted.

Champion, H.G. and Griffith, A.L. 1948. Manual of general silviculture for India. Geoffrey Cumberlege, Oxford University Press (UK).
India: Management, textbook
Important reasons for failures with mixed plantations are summarised. Limited present knowledge means that work must probably be experimental for many years to come. Evidence indicates that benefits from mixtures must be derived from the maintenance of soil over future rotations.

Chapman, K., Whittaker, J.B. and Heal, O.W. 1988. Metabolic and faunal activity in litters of tree mixtures compared with pure stands. Proceedings: Workshop on interactions between soil-inhabiting invertebrates and microorganisms in relation to plant growth, Columbus, Ohio, March 1987. In: Agriculture, Ecosystems and Environment V. 24 (1-3), Elsevier, 1988.
UK: Soils
Vis-à-vis single species stands, nutrient availability and tree growth were enhanced in spruce/pine and depressed in spruce/alder and spruce/oak mixtures. Mobilization rates were correlated positively with metabolic activity, and related to changes in the decomposer community of the forest floor.

Chaturvedi, A.N. 1983. Eucalyptus for Farming. Uttar Pradesh Forest Bulletin 48. 48pp

India: Management
Suppression inevitably occurs in a mixture. Eucalyptus tends to suffer more from competition. 9 mixtures have been tried and rejected.

Chijioke, E.O. 1980. Impact on soils of fast-growing species in lowland humid tropics. André Mayer Research Fellowship. FAO Forestry Paper 21, FAO, Rome.
Tropics: Soils
No evidence that monoculture leads to a more rapid depletion of the soil nutrient reserves than would mixtures having the same biomass production, rotation length and the same proportion of the crop removed in harvesting.

Chou, C.K.S. 1981. Monoculture, species diversification, and disease hazards in plantation forestry. New Zealand Journal of Forestry 26 (1): 20-42.
New Zealand: Environmental, Pests and diseases
The issue of stand composition and disease hazard is unclear. If a pathogen has several host species, mixtures may be no safer than pure stands. This makes prescription of safe mixtures hard. Regimes for mixed stands may by themselves create disease problems. Crop rotation is a form of mixture that may prove necessary.

Chu, C.G.1980. (Study on biological productive forces of *Pinus koraiensis* artificial forest.) Institute of Forestry and Pedology, Academia Sinica.
China: Yield
Pure and mixed stands of *Pinus koraiensis* are compared. Total biomass when mixed with broadleaves is higher than in pure stands. Quality and vigour of mixed stands is also higher.

Ciesla, W.M. 1991. Cypress aphid: a new threat to Africa's forests. Unasylva 167. Vol.42: 51-55.
Eastern Africa: Insect attack
Account of attacks to *Cupressus lusitanica* by *Cinara cupressi*.

Ciesla, W.M. and J.E. Macias Samano. 1987. Desierto de los Leones: A forest in crisis. American Forests 93: 29-31, 72-74.
Environment: Pollution

Clatterbuck, W.K., Oliver, C.D. and Burkhardt, E.C. 1987. The silvicultural potential of mixed stands of cherrybark oak and American sycamore: Spacing is the key. Southern Journal of Applied Forestry 11: 158-161.
USA: Management
Line mixture of *Quercus falcata var. pagodifolia, Platanus occidentalis* and *Populus deltoides*(died out). *Q. falcata,* the more valuable species, was suppressed by neighbouring *P. occidentalis*. At 24 years dominant *Q. falcata* caught up with *P. occidentalis*. Management obviously important.

Clatterbuck, W.K. and Hodges, J.D. 1988. Development of cherrybark oak and sweet gum in mixed, even-aged bottomland stands in central Mississippi, USA. Canadian Journal of Forest Research 18(1): 12-18.
USA: Yield. Management
"Restricted" development occurred at a spacing of 5.5 m. *Liquidambar styraciflua* dominated for 20 years. By age 58 *Q. falcata* had a dbh of 61 cm and a height of 34 m. "Unrestricted" development occurred where dominants or codominants were more than 5.5 m apart. Then *Q. falcata* achieved 56 cm dbh and 26 m in height at age 40.

Clout,M.N. 1985. Wildlife in pine plantations - the New Zealand position. In: Wildlife management in the forests and forestry controlled lands in the tropics and southern hemisphere. ed J.Kikkawa. IUFRO Workshop held at University of Queensland, Australia.

Tropics and southern hemisphere: Wildlife
Diversity of native bird species is positively correlated to structural habitat diversity. Young pine plantations are particularly poor habitats for native birds.

Cossalter, C. 1991. Personal communication.

Coster, C. 1934. *Rapport over de reboisatie der Tegal-Waroe landen.* (Report of the reafforestation of the Tegal Waru lands 1934.) Unpublished. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 626.
Indonesia: Management
Recommendations of methods to reafforest grasslands. Mixtures with *Albizia falcataria* in the top storey is among the methods recommended.

Coté, B. and Camire, C. 1987. Tree growth and nutrient cycling in dense plantings of hybrid poplar and black alder. Canadian Journal of Forest Research 17 (6): 516-523.
Canada: Soils
Alnus glutinosa and *Populus nigra* x *P. trichocarpa*. Stimulatory effect of alder on poplar growth decreased over three years. Reduced competition of the smaller alder for soil N and light in the first growing season is considered the most important factor in increasing individual poplar growth.

Courrier, G. and Garbaye, J. 1981. *A propos de la sylviculture des peuplements mélanges. Un exemple de l'effet benefique de l'aulne sur la croissance des peupliers.* Revue Forestier Française 33 (4): 289-292.
France: Soils
Fertilizer effects on *Populus* "Fritzi Pauley" had completely disappeared after 10 years, but there was strong correlation between poplar volume and number of *Alnus glutinosa.*

Craib, I.J. 1947 The silviculture of exotic conifers in South Africa. Journal of the South African Forestry Association 15: 11-45.
South Africa: Management
Recommendations for heavy early thinnings in conifers to maximise economic returns.

CTFT 1977 (?). *Projet de plantation du framiré en mélange avec d'autres essences (fraké, samba, cedrela, ou cordia). Proposé à la Direction de Reboisement de la SODEFOR.* CTFT Division d'Entomologie et de Pathologie Forestières (unpublished).
CTFT: Management, regeneration, spacing
It has been found that efforts at raising *Terminalia ivorensis* are more successful when they are raised at low densities. To keep up profitability, mixtures have been tried.

CTFT 1991. *Essais: Composition de peuplement "mélange d'essences"* (Experiments: Mixed stands). Unpublished. CTFT, Nogent-sur-Marne.
West Africa (+ Madagascar, French Guyana, New Caledonia); Management, Yields
A summary of each of 63 experiments (active or closed) mainly in 8 West African francophone countries.

Darrah, G.V. and Dodds, J.W. 1967. Growing broadleaved trees in mixture with conifers. Forestry 40 (2): 220-228. UK.
UK: Management
Compatibility between species, or provenances, is important to the success of a mixture. Yields of conifers are often less than optimal because thinnings occur at inconvenient times, especially if the mix is incompatible.

Darroze, S. 1991. Personal communication.

Davidson, J. 1986. Underplanting, interplanting and buffer planting for forest plantations. Assistance to the Forestry Sector of Bangladesh. UNDP/FAO Project BGD/79/017. Working Paper 18. Bangladesh: Management Underplanting of ground cover crops is advocated. Examples of successful legumes are given. Two species mixtures with one legume are recommended.

Dawkins, H.C. 1949. Timber planting in the *Terminalia* woodland of Northern Uganda. Empire Forestry Review 28 (3): 226-246.
Uganda: Management
Establishment of *Chlorophora excelsa* and *Khaya grandifoliola* in a matrix of *Phyllanthus discoideus* and *Gmelina arborea*. An analysis of ecological succession in a dry (5 months dry season) site from fire-prone *Terminalia* grassland to fire tender spp - *Entandrophragma angolense* etc.

Dawson, J.O., Dzialowy, P.J., Gertner, G.Z. and Hansen, E.A. 1983. Changes in soil nitrogen concentration around *Alnus glutinosa* in a mixed, short-rotation plantation with hybrid *Populus*. Canadian Journal of Forest Research 13(4): 572-576.
USA: Soils
In a 4-year-old mixed plantation N accretion was greatest in alder:poplar 1:1 plantations, less in 2:1 mixture and least in 3:1 mix. It is hypothesised that early accretion of N in soil results from competition-induced stress resulting from shading by poplars or poplar allelochemicals.

DeBell,S.D., Whitesell,C.D. and Schubert,T.H. 1985. Mixed plantations of Eucalyptus and leguminous trees enhance biomass production. Research Paper PSW-175. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, US Dept. of Agriculture. pp 6.
Hawaii: Yield. Soils
N-fixing species, *Acacia melanoxylon* and *Albizia falcataria*, were grown in line mixtures of *Eucalyptus grandis* and *E. saligna*. At 65 months height growth of eucalyptus was greater in mixtures with *Albizia*. Foliar nutrient concentrations were higher, and soil nutrients lower, in the mixtures.

DeBell, D.S., Whitesell, C.D. and Crabb, T.B. 1987. Benefits of *Eucalyptus-Albizia* mixtures vary by site on Hawaii Island. Research Paper PSW-187. Berkeley, CA. Pacific Southwest Forest and Range Experiment Station, Forest Service, US Dept. of Agriculture.
pp 5.
Hawaii: Yield. Management
Inorganic fertiliser applied to pure and mixed plantations. Admixture of *Albizia falcataria* into *Eucalyptus saligna* plantations improved eucalyptus growth on the two wetter sites, but not on the two drier sites. On one site the *Albizia* failed. Failure attributed to low rainfall. *Acacia mangium* may be an alternative to *Albizia*.

DeBell, D.S., Whitesell, C.D. and Schubert, T.H. 1989. Using N_2-fixing Albizia to increase growth of Eucalyptus plantations in Hawaii. Forest Science 35 (1): 64- 75.
Hawaii: Soils. Yield
In comparison to pure (heavily fertilised) eucalyptus (94 t/ha dry matter) those mixtures with 11 and 25% Albizia depressed yield by up to 29%; higher proportions of Albizia increased yields by up to 12%. But even the plot with the lowest yield (67 t - 11% Albizia) had a higher yield than pure eucalyptus (outside the experiment) receiving standard fertilizer application (yield 44 t).

Delwaulle, J.C. 1989. *Plantations clonales au Congo. Point des recherches sur le choix des clones dix ans après les premières plantations.* In: Gibson, G.L., Griffin, A.R. and Matheson, A.C. (eds). Proceedings of a Conference on Breeding Tropical Trees: Population Structure and Genetic Improvement Strategies in Clonal and Seedling Forestry, held in Pattaya, Thailand, 28 November - 3 December 1988. IUFRO WPs S2.02-08 and S2.02-09.Oxford Forestry Institute, UK. 431-434.
Congo: Management

Delvaux, J. 1971. (Pure or mixed stands.) Bull. Soc. For. Belg. 78 (4): 183-197.
Reviewing article
A general discussion on the merits and drawbacks of mixed and pure stands.

Deventer, A.J. van. 1913. *Gemengde djatibosschen (prae-advies).* Mixed teak forests (proposals).) Tectona 6: 273-293. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 600.
Indonesia: Soils
A cover crop in a teak plantation must give soil protection, be shade tolerant, never overgrow the teak, and yield a marketable product. Kesmabi (*Schleichera oleosa*) is recommended for this.

Donaubauer, E. 1991. Plantation Management: Aspects of Resistance and Resilience to Pests, Diseases and Abiotic Factors. Unpublished report for FAO.
General: Pests and Diseases
A review of the literature.

Dransfield, J. 1977. *Calamus caesius* and *C. trachycoleus* compared. Gardens' Bulletin, Singapore 30: 75-78.
Indonesia: Management
Calamus caesius, a rattan species, can be completely harvested twice, at 7-10 years and 4 years later, before exhaustion. This fits in with a shifting cultivation system where at least 14 years fallow needed. But if selective cutting is used, the plant's life is very much longer. *C.trachycoleus* has longer stolons and it therefore establishes itself.

Dransfield J. 1988. Prospects for rattan cultivation. Advances in Economic Botany 6: 190-200.
Malaysia/Indonesia: Management. Yield. Economy
Heavy shade results in poor growth, but longer internodes which is desirable. Canes can be cultivated in secondary forest, poor quality rubber plantations or under pines.

Duff, A.B., Hall, R.A. and Marsh, C.W. 1984. A survey of wildlife in and around a commercial tree plantation in Sabah. The Malaysian Forester 47 (3): 197-213.
Malaysia (Sabah): Wildlife
Wildlife damage can be reduced by separating natural forests and plantations, or by planting unpalatable species at the boundary to the natural forest. Islands of natural forests are beneficial to predators. Mammal presence is higher where ground cover is available.

Dunikowski, S. 1991. *Protection des forêts contre les agressions biotiques et abiotiques.* Position Paper, Theme 4, 10th World Forestry Congress, Paris, 1991. Proceedings, Vol.2: 285-290.
General: Environment
Need to transform pure conifer stands, which are susceptible to damage from atmospheric pollution, into mixed stands with a high proportion of broadleaved trees.

Dupuy, B. 1985. *Plantations à vocation bois d'oeuvre et associations d'espèces en mélange: objectifs et contraintes sylvicoles.* CTFT, Côte d'Ivoire (unpublished).
Côte d'Ivoire: Management, Yields

Dupuy, B. 1986. (The main silvicultural rules for timber production plantations.) CTFT, Côte d'Ivoire (unpublished draft).
Côte d'Ivoire: Management
Mixtures can be classified into those made up of one main species and one with a cultural role, and those consisting of species of equal silvicultural importance. Possible associations and regimes are discussed.

Dupuy, B. 1989a. *Etude de mélange: Gmelina arborea/Acacia auriculiformis.* CTFT (unpublished).
Côte d'Ivoire: Management
4 mixtures of *G. arborea/A. auriculiformis* were tested, 50, 33, 20 and 10% of acacia. *Gmelina* outgrew the acacias, except in the 10% mixture. In this kind of mixture firewood can be collected after 5 to 6 years, while the dominant species is allowed to grow.

Dupuy, B., 1989b. *Sylviculture des peuplement en mélange fraké/framiré.* CTFT, Côte d'Ivoire (unpublished).
Côte d'Ivoire: Management. Yield
Mixtures of *Terminalia ivorensis/Terminalia superba,* 50/50, 25/75 and 6/94%, were compared. Rate of mixture does not appear to affect growth of either species. Silvicultural methods depend on which species is to be favoured in the thinnings.

Durigan, G. and de Souza Dias, H.C. 1990. *Abundancia e diversidade da regeneracao natural sob mata ciliar implantada.* Instituto Florestal, Sao Paulo, Brazil. Mimeographed Paper presented to 6th Congresso Florestal Brasiliero.
Brazil: Management
Regeneration under riparian forest planted 1973 (17 years old) in Candida Mota-SP. 150 species planted, 41 other spp. regenerated naturally. Only a few planted species regenerated, these included exotics. Generally low species diversity in regeneration, tending to a homogenous forest in the next succession stage.

Durigan, G. and Nogueira, J.C.B. 1990 *Recomposicao de matas ciliares.* Instituto Florestal Serie Registros, Sao Paulo 4: 1-14.
Brazil: Management
Lists appropriate species for creating natural forests on river banks and classifies them by their ecological requirements and position in ecological succession.

Earl, D.E. 1968. Latest techniqes in the treatment of natural high forest in South Mengo District. Paper to 9th Commonwealth Forestry Conference, India.
Uganda: Management
The use of charcoal burning as a management tool in natural forest management.

Eidmann, F.E. 1932. *Het onderplantingsvraagstuk van den djati.* (The problem of underplanting teak.) Korte Meded. B.P.S. 27 and Tectona 25: 671-690, 1628-1682. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982, Abstract 984.
Indonesia: Management
It is expected that the only successful way of underplanting teak will to thin regularly and heavily to open the canopy and at the same time introduce a shade tolerant, deep rooting species that will produce valuable wood.

Evans, J. 1975. Two rotations of *Pinus patula* in the Usutu forests, Swaziland. Commonwealth Forestry Review 54 (1): 69-81.
Swaziland: Yield
A slight increase in second rotation yield noted and attributed to better than average rainfall and reduced grass competition at time of establishment.

Evans, J. 1978. A further report on second rotation productivity in the Usutu forest, Swaziland - results of the 1977 reassessment. Commonwealth Forestry Review 57 (4): 253-261.
Swaziland: Yield
Average rainfall was 1230 mm. Late arrival of spring rains 1974-6 can be detected in growth rates (reports of drought-induced deaths). Reports on yields obtained from the second rotation or later are reviewed.

Evans, J. 1987. Site and species selection - changing perspectives. Forest Ecology and Management 21: 299-310.
The tropics: Management. Yield
Reviews the need for the use of appropriate species, including the appropriateness for the end use, including village use. An analysis of plantation species used in the tropics in order of frequency, excluding southern China.

Evans, J. 1988. The Usutu forest: 20 years later. Unasylva 159 (40): 19-29.
Swaziland: Yield. Management
Low rainfall in 1958-65 and 1978-82 is a confounding factor in comparing yields. Fertility losses may be due to nutrient drain through biomass removals, alteration of soil characteristics or compaction and erosion resulting from the extraction. 15% of the area is on gabbro rock formations and here phosphate reserves may have been critically depleted.

Evans, J. 1990. Long-term productivity of forest plantations - status in 1990. Procedings of IUFRO XIX World Congress, Montreal. Vol 1: 165-181.
Tropics; Management, Soils
A review of yields attained in later rotations.

Ewel, J.J. 1986. Designing agricultural ecosystems for the humid tropics. Annual Review of Ecology and Systematics 17: 245-271.
The tropics: Soils
A general review of the literature. Deep rooted species increase the soil volume exploited. N fixers may use the N themselves and only make it available through leaf fall. Organic matter accounts for up to 50% of total P in surface horizon of tropical soils.
Organic P circulates rapidly.

FAO. 1988. An interim report on the state of forest resources in the developing countries. Forestry Department FO:MISC/88/7, FAO, Rome.
The tropics: Management
An analysis of forest types and plantations as at 1980 with planting estimates for 1981 to 1985.

FAO, 1991a. Exotic aphid pests of conifers: A crisis in African forestry. Workshop Proceedings, FAO/Kenya Forestry Research Institute, June 1991

FAO. 1991b. *Les plantations à vocation de bois d'oeuvre en Afrique intertropicale humide.* FAO Forestry Paper 98.
West Africa: Management
A silvicultural manual with a chapter on mixtures.

Farrichon, V. 1987. *Résultats des études menées au projet AFRI d'avril 1986 à mai 1987. Comparaison de deux espèces d'eucalypts (E. tereticornis et E. torelliana) utilisées au projet AFRI.* CTFT (unpublished).

Togo: Yield
In a line mixture of *E. tereticornis* and *E. torreliana, E. tereticornis* has proved to be the more competitive of the two.

Ferguson, I.S. 1983. Plantation Management in Australia. New Zealand Journal of Forestry 28 (3): 327-338.
Australia: Management
An analysis of national forest policy in relation to plantation establishment and the need for understanding marketing issues; includes a statement of areas under various tree crops.

Ferguson, J.H.A., Hellinga, G. and Alphen de Veer, F.J. van. 1949. *Eenige gedachten over de Pinus kultur in Indonesie.* (Some ideas about the cultivation of pines in Indonesia.) Tectona 39: 383-387. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 584.
Indonesia: Management, cover crop
To avoid the risks of pure plantations when establishing plantations of *Pinus merkusii,* mixing with *Swietenia macrophylla* on the plains, and with *Agathis loranthifolia* in the mountains on not too poor soils is discussed.

Florence, R.G. 1967. Factors that may have a bearing upon the decline of productivity under forest monoculture. Australian Forestry 31: 51-71.
General: Soils
Analysis of factors that may lead to a long term decline in productivity.

Florence, R.G. and Lamb, D. 1974. Influence of stand and site on Radiata pine litter in South Australia. New Zealand Journal of Forest Science 4 (3): 302-310.
Australia: Soils
Litter accumulation related more to soil type than to site quality and to rate of decomposition than to rate of fall.

Francis, P.J. and Shea, G.M. 1987. Management of tropical and sub-tropical pines in Queensland. In Forest Management in Australia; Proceedings of a Conference of the Institute of Foresters of Australia pp 273-280.
Australia: Management

Franzini, F. 1957. *Les reboisement artificiels dans les savanes de la région de Pointe Noire.* (Afforestation of savannah land in the Pointe Noire region.) Bois et Forêts des Tropiques 53: 25-32.
Congo: Management
Experiments in afforestation of savannas with *Eucalyptus saligna, Eucalyptus camaldulensis* and *Casuarina equisetifolia* are described.

Friedrich, J.M. and Dawson, J.O. 1984. Soil nitrogen concentration and *Juglans nigra* growth in mixed plots with nitrogen-fixing *Alnus, Elaeagnus, Lespedeza* and *Robinia* species. Canadian Journal of Forest Research 14 (6): 864-868.
USA: Soils
In a 14-year-old plantation with spacings of 3.7x4.9 and 9.8m, the highest total soil N concentration in top 30 cm was under closely-spaced *Elaeagnus* and both spacings of *Robinia* (girdled). Walnut basal area was not strongly correlated with soil nitrogen concentration.

Friend, G.R. 1980. Wildlife conservation and softwood forestry in Australia: some considerations. Australian Forestry 43 (4): 217-224.
Australia: Wildlife
Radiata plantations are specialised and simplified habitats. They are impoverished in that they lack diversity in wildlife. Animals without specialist requirements are least affected, even favoured, by plantations. Measures to counter this impoverishment are discussed

Frivold, L.H. 1982. *Blandningsskogens status i europeiskt skogsbruk.* (Status of mixed forests in European forestry.) Tidsskrift foer skogsbruk 90 (3): 250-261.
Europe: Reviewing article
Most investigations of the "mixed species effect" cannot positively rule out site differences. Investigations concluding that spruce monocultures lead to soil degradation deserve attention. Experience suggests certain mixtures raise timber quality. Pure stands may be more sensitive to calamities than mixed, stand vigour may also play a role in this. Mixed stands are probably more wind resistant.

Frivold, L.H. 1985. Mixed broadleaved stands - Some silvicultural considerations. In: Broadleaves in Boreal Silviculture - An Obstacle or an Asset? Swedish University of Agricultural Sciences, Report 14.
Boreal forests: Reviewing article
A "mixed species effect" cannot be ruled out. The effect is probably not greater than a few percent. Data on the relationship between stability and diversity are few. Mixed stands may, in some cases, be more stable than pure. Evidence regarding sustainability and mixtures is contradictory.

Garrido,M.A. and Poggiani,F. 1979. *Caracteristicas silviculturais cinco especies indigenas plantadas em povoamentos puros e mistos.* (Silvicultural characteristics of five indigenous species in pure and mixed stands.) Silvicultura em Sao Paulo 13/14 pp 33-44.
Brazil: Management
5-year growth statistics for *Piptadenia macrocarpa, Astronium urundura, Moquinia polymorpha, Colubrina rufa* and *Tabebuia impetiginosa* grown pure and mixed. *P.macrocarpa* had better dbh and height growth than the mixture as a group. Of the individual species only *C.rufa* and *T.impetiginosa* did better in mixture.

Geldenhuys, C.J. 1975. *Die kunstmatige verstiging van inheemse bos in die Suid-Kap.* (The artificial establishment of indigenous forest in the southern Cape.) Bosbou in Suid Afrika 16: 45-53.
South Africa: Management
The taungya system was used to establish ten species of the Cape indigenous forest. Stem number and survival was higher than in an adjacent forest under production management.

Gepp, B.C. 1976. Bird species distribution and habitat diversity in an exotic forest in south Australia. Australian Forestry 39 (4): 269-287.
Australia: Wildlife
Pine plantations, native forests and grasslands were compared as to bird habitats. Lowest diversity occurred in the interior of unthinned plantations. The number of species in the plantations was almost the same as in the native vegetation. The landscape mosaic seems to provide niches enough for most species in the area.

Gepp, B. 1985. Values of wildlife in forest plantations in the tropics and southern hemisphere. In Wildlife Management in the Forests and Forestry Controlled Lands in the Tropics and Southern Hemisphere. ed J.Kikkawa. IUFRO Workshop held at University of Queensland, Australia.
General: Wildlife
Conditions in plantations change. The pole stage (app. 20% of the rotation) is the most uniform stage, and least suited to wildlife. Wildlife in plantations favours areas with native regeneration. Retention of islands or a mosaic of native species is helpful. Plantations on farm or grassland may raise diversity.

Gibson, I.A.S. and Jones, T. 1977. Monoculture as the origin of major forest pests and diseases, especially in the tropics and southern

hemisphere. Origins of Pest, Parasite, Disease and Weed Problems. ed Cherrett, J.M and Sagar, G.R. Blackwell, Oxford (UK) pp 139-161.
General: Environmental, pests and diseases
Diseases in monocultures are more numerous for species growing in their native range than for exotics. Plantation forestry allows for more expenditure on protection measures than other kinds of forestry.

Gilmour, D.A., Ingles, A. and Maharjan, M.R. 1989. Preliminary harvesting guidelines for community forests in Sindhu Palchok and Kabhre Palanchok. Technical Note 2/89, Nepal Australia Forestry Project, Kathmandu 9p.
Nepal: Management: Social
Prescriptions for the management, by village communities, of coppice-with-standards, mixed and single species high forest, including pine-broadleaved mixtures.

Gilmour, D.A., King, G.C., Applegate, G.B. and Mohns, B. 1990. Silviculture of plantation forest in central Nepal to maximise community benefits. Forest Ecology and Management 32: 173-186.
Nepal: Management. Yields. Social
A trial of management techniques for *Pinus roxburghii* plantations in which mixed broad leaved species (predominantly *Schima wallichii)* have regenerated. The objective has been to devise techniques that will result in sustainable yield of products that the villagers require.

Gonggrijp, L. 1929. *Doelbewuste kunstmatige menging van djati en wildhout.*(Artificial mixing of teak with other trees.) Tectona 22: 1287-1294. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 592.
Indonesia: Economy
The author feels that the necessity of mixtures is unproven, and that the economy of mixing has received too little attention.

Graham, R.M. 1945. Notes on the growing of cypress timber on farms. East Africa Agricultural Journal 11: 132-139.
Kenya: Soils. Environmental, pests and diseases
Grevillea robusta is considered suitable for mixture with *Cupressus macrocarpa*. This is done to avoid hazards with monoculture e.g. soil degradation, pests and diseases.

Graham, R.M. 1949. Plantation management order no. 5. *Grevillea robusta*. Forest Department, Colony and Protectorate of Kenya.
Kenya: Management
Considerable quantities of *Grevillea robusta* have been grown in mixture with cypresses and other species. The species is worth growing for its own sake. A regime is suggested.

Granert, W.G. and Cadampog, Z. 1980. *Leucaena* as a nurse tree. Leucaena News Letter 1: 21.
Philippines: Management
Teak and mahogany (*Swietenia macrophylla*) planted with ipil-ipil (*Leucaena leucocephala*). No effect on the growth of teak was observed, but it was considered straighter. No growth improvements noted for mahogany either, but incidence of tip borer attacks was reduced under ipil-ipil.

Gray, B. 1972. Economic tropical entomology. Annual review of Entomology 17: 313-353.
Tropics: Pests

Grijpma, P. 1973. Immunity of *Toona ciliata* Roem. var *australis* (F.v.M)C.D.C. and *Khaya ivorensis* A.Chev. to attacks of *Hypsipyla grandella* (Zeller) in Turrialba, Costa Rica. In Studies on the Shootborer *Hypsipyla grandella* (Zeller) Lep. Pyralidae Vol. I Inter-

American Institute for Cooperation on Agriculture (IICA) Misc. Pub. 101 p 18-25.
Tropics: Pests
H.grandella (New World) and *H.robusta* (Old World) appear to be relatively specific to indigenous Meliaceae; *Swietenia macrophylla* in India and Sri Lanka and *Khaya ivorensis* in Martinique are exceptions.

Grijpma, P. and Ramaldo, R. 1973. *Toona spp posibles alternativas para el problem del barrendor Hypsipyla grandella de los Meliaceae en America Latina.* In Studies on the Shootborer *Hypsipyla* (Zeller) Lep. Pyralidae Vol. I. Inter-American Institute for Cooperation on Agriculture (IICA) Misc. Pub. 101 p 3-17.
Central America: Pests
T.ciliata though heavily attacked by *H.robusta* in Australia is not attacked by *H.grandella* in Costa Rica.

Groulez, J. 1975. *Notes sur les plantations de conversion dans les forêts tropicales humides.* (A note on conversion plantations in moist tropical forests.) Bois et Forêts des Tropiques 162: 3-26.
Tropics: Management
Discusses the pros and cons of conversion plantations (that is, replacing the natural forest) and despite problems of costs and lack of profitability considers them promising. 26,000 ha *Aucumea klaineana* in Gabon, 6,000 ha *Terminalia superba* in Congo, 50,000 ha *Gmelina* in Brazil.

Grutterink, B.J. 1930. *Verslag van de excursie op 21 maart 1930 naar de boscomplexen Watoetoetoek, Pantodomas en de sagerij Sapoeran der Firma J.v.d. Welle.* (Report of the excursion on 21 March 1930 to Watoetoetoek and Pantodomas forest complexes and the Dapuran sawmill of the firm J.v.d. Welle.) Tectona 23: 633-640. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 593.
Indonesia: Soils
Mixtures of shade-tolerant species are to be preferred from the hydrological point of view. Planting light demanders means that a good protection forest will not be formed.

Guizol, P. 1985. *Les plantations mélangees.* Ecole Nationale du Génie Rural des Eaux et des Forêts, France, pp. 18.
France: Management
A survey of mixed stands in France. Advantages of mixing are listed, and suitable mixtures recommended.

Guizol, P. 1983/85. *Les plantations mélangees.* Mixed plantations. Elève-Ingénieur Civil de Forêts, Promotion. Ecole Nationale du Génie Rural, des Eaux et des Forêts.
France: Management
A survey of mixed stands in France. Comparisons are made to see what mixtures gave the best results. Objectives of mixing are discussed.

Hägg, A. 1988. *Loensamheten av bjoerkinblandning i barrskog.* (The profitability of a birch admixture in coniferous forests.) Swedish University of Agricultural Sciences, Department of Forest Products, Report No. 208.
Sweden: Economy
It is profitable to retain birches to increase stand density. Birch admixture raises the quality of pines. Selective removals of birch in mature stands can be increased. Costs for this are counterbalanced by lower future tending costs.

Hägg, A. 1989. *Bjoerkens inverkan paa tallens grengrovlek och grenrensning i blandade bestaand.* (The influence of the birch upon the

branch diameter and the self-pruning of pine trees in mixed stands.) Swedish University of Agricultural Sciences, Department of Forest Products, Report No. 208.
Sweden: Management. Economy
Increase in stand density caused by naturally regenerated birches results in a lower branch diameter of the butt log. If birches are retained after cleaning operations this effect is enhanced and self-pruning increased.

Hägg, A. 1990. *Loensamheten av att anvaenda sjaelvfoeryngrad bjoerk foer kvalitetsdaning av planterad tall.* (The profitability of using self-regenerated birch for shaping the quality of the planted pine.) Swedish University of Agricultural Sciences, Department of Forest Products, Report No. 214.
Sweden: Economy. Management
Branch diameter of pines depends on stand density, not on mixtures. Retaining 1400 and 7900 birches/ha. is compared. Calculations show that retaining birch is profitable, this is enhanced by fertilization after 50 years. For the regime of 7900 birches to be the more profitable, it must produce 38% more of prime grade timber than the other.

Hansen, E.A. and Dawson, J.O. 1982. Effect of *Alnus glutinosa* on hybrid *Populus* height growth in a short rotation intensively cultured plantation. Forest Science 28 (1): 49-59.
USA: Yield. Soils
In a 3-year-old line mixture, poplar height increased with the share of alder, and decreased with distance between the two species. In a neighbouring stand significant N accretion occurred up to 15 cm from alder stems.

Harencarspel, W. van 1908. *Menging van lichtbehoeftige met sterk beschaudwende houtsoorten.* (The mixing of light demanding tree species with tree species producing shade.) Tectona 1: 182-184. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982, Abstract 594.
Indonesia: Management
Group mixing *Cupressus* and *Casuarina* with species that will not grow tall is to be preferred to individual mixing.

Harrington, C.A. 1982. Sitka alder, a candidate for mixed stands. Canadian Journal of Forest Research 12 (1): 108-111.
Canada: Management
Analysis of height growth pattern (max. 5m in 14 years) suggests that *Alnus sinuata* may be a suitable nurse for *Pseudotsuga menziesii,* but advance planting of large *P.menziesii* is the stock advisable on poor sites.

Hart, H.M.J. 1931a. *Gemengde djaticulturen, deel I+II.* (Mixed teak plantations Part I and II.) Meded. P.v.h.B. 24: pp 170 (part I) and pp 400 (part II). Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982, Abstract No. 602.
Indonesia: Management. Soils
It is concluded that mixing is favourable only under special circumstances. In most cases examined mixing proved to be unfavourable.

Hart, H.M.J. 1931b. *Gemengde djaticulturen.* (Mixed teak plantations (proposal).) Tectona 24: 88-107. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 603.
Indonesia: Management
Most of the supposed beneficial effects of mixing have proved to be unfounded. Intensive soil cultivation stimulates the growth of young teak. Interplanting of leucaena may have the same effect.

Hart, H.M.J. 1931c. *Gemengde djaticulturen.* (Mixed teak plantations (explanation and discussion).) Tectona 24: 488-511. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 604
Indonesia: Management
The poorer the soil the more adverse is the influence of mixing. Natural pruning is better in pure teak plantations.

Hart, H.M.J. and Noltée, A.C. 1927. *Verjonging en verpleging van den djati.* (Regeneration and tending of teak.) Tectona 20: 199-213. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 568
Indonesia: Management
A historic survey of regeneration techniques for teak.

Hasan, S.M., al Saraf, M.J. and Khalil, M.T. 1980. (Comparative studies on the growth of *Pinus brutia* in pure and mixed plantations.) Mesopotamia Journal of Agriculture (from Forestry Abstracts Vol.42 2949).
Iraq: Yield
Pure *Pinus brutia* was compared to *P.brutia* interplanted with *Acacia farnesiana*. After three growing seasons height growth was significantly higher in the mixed stand.

Heald, R.C. and Haight, R. 1979. A new approach to uneven-aged silviculture and management of mixed conifer-oak forests. California Agric. 33 (5): 20-22.
Management
A method of identification of vegetation types is presented. Management is directed at maintaining these types.

Heilman, P. and Stettler, R.F. 1985. Mixed short rotation of red alder and black cottonwood: Growth, coppicing, nitrogen fixation and allelopathy. Forest Science 31 (3): 607-616.
North America: Soils. Yield
Beneficial effects of mixing with red alder cannot be ruled out by this study.

Henry, P.W.T. 1960. The Akilla plantation. Inform. Bull. Dep. For. Res. Nigeria 9: 1-4.
Nigeria: Management
Of the species tried for planting in tropical lowland rain forest, the greatest success has been achieved with *Nauclea diderichii*, pure or in 5/1 mixture with *Meliaceae*.

Heybroek, H.M. 1980. Monoculture versus mixture: interactions between susceptible and resistant trees in a mixed stand. In: Resistance to diseases and pests in forest trees, Proceedings of the Third International Workshop on the Genetics of Host-Parasite Interactions in Forestry, Wageningen, September 1990. PUDOC, 1982. pp 20.
General: Environmental, pests and diseases
Mixing of hosts and non-hosts to diseases may be effective, but as it often means mixing species, it may entail silvicultural problems. Mixing of genotype is a poor substitute for breeding for resistance.

Heybroek, H.M. and Tol, G. van 1985. Experiences with genetically mixed forest plantations in the Netherlands. Forest Ecology and Management 12: 155-162.
The Netherlands: Management
Mixtures are difficult to maintain over rotations, they often develop into more or less pure stands, or mosaics thereof. In clonal forestry, a mosaic of pure stands is preferable to individual mixtures.

Hirano, R.T. 1990. Propagation of *Santalum*, Sandalwood tree. In Proceedings of the Symposium on Sandalwood in the Pacific, April 1990, Honolulu, Hawaii. US Department of Agriculture, Forest Service, General Technical Report PSW-122. p43-45.

Hawaii: Management
A brief description of Sandalwood trade in Hawaii and notes on nursery practice.

Ikemori, Y.K. 1990. Genetic variation in characteristics of *Eucalyptus grandis* (Hill) Maiden raised from micro-propagation, macro-propagation and seed. D.Phil thesis, University of Oxford (UK).
Brazil: Yields
Average yield has been raised from 30 to 45m^3/ha/yr with anticipation of raising to 55m^3. Specific wood consumption should be reduced from 4.2m^3/tonnes pulp to 3.7m^3.

Indian Forest Service 1934. Fourth Silvicultural Conference, Item 8. Dehra Dun, India.
India: Management
A document discussing mixed plantation at some length.

Indian Forest Service 1939. Fifth Silvicultural Conference, Item 14, Dehra Dun.
India: Management
This document contains one of the most detailed discussions encountered on the subject.

Ingles, A. 1990. Demonstration of forest management options in shrublands and mixed pine - broadleaf forests. Discussion Paper of Nepal-Australia Forestry Project, Kathmandu. pp 47.
Nepal: Social. Management. Yields
Management options for different vegetation types are suggested.

Ishibashi, H. 1987. The development and problems in the anti-erosion plantations in Japan. Mitteilungen der Forstlichen Bundes-Versuchanstalt, Wien, No. 138.
Japan: Soils
Terraces are planted with a mixture of *Pinus thunbergii* and *Alnus pendula*. Big areas have developed into stands of little or no pine, which erode and need intensive treatment; the regime is described.

Japing, H.W. about 1931. *Het verjongingsonderzoek van sandelhout (Santalum album) op Jawa*. (Research on the regeneration of sandalwood (*Santalum album*) in Java. Unpublished. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 638.
Indonesia: Management
Brief presentation of trials to raise sandalwood in mixture.

Jones, A.D., Davies, H.I. and Sinden, J.A. 1990. Relationships between eucalypt dieback and land use in southern New England, New South Wales. Australian Forestry 53 (1): 13-23.
Australia: Environmental: Pests and diseases
An analysis of a time series of aerial photographs using associations in multiway tables. No clear relationship could be detected between increased species diversity and reduction in dieback.

Jones, E.W. 1945. Structure and reproduction of the virgin forests of the north temperate zone. New Phytologist 44: 130-148.
North temperate: Ecology

Jones, E.W. 1965. Pure conifers in central Europe - A review of some old and new work. Journal of Oxford University Forestry Society 13: 3-15
Europe: Management
Important works concerning the subject are reviewed.

Jones, P.D and Wigley, T.M.L. 1990. Global warming trends. Scientific American 263 (2): 66-73.
General: Environmental

A "greenhouse" mathematical model has predicted that the warming in the last century should have been .5 to 1.3° C and will be +4° C by the year 2050. The model does not fit the facts as known exactly - 1920-40 warmer than predicted; 1940-70 cooler.

Jonsson, B. 1961-62. *Om barrblandskogens produktion.* (Yield of mixed coniferous forests.) Meddelanden fran statens skogsforskningsinstitut, 50.
Sweden: Yield
Results indicate that mixtures affect yield. The effect is greatest on sites suited to both *Pinus silvestris* and *Picea abies.* In either direction the effect diminishes, finally becoming negative.

Jordan, C.F. and Farnworth, E.G. 1982. Natural versus plantation forests. A case study of land reclamation strategies for the humid tropics. Environmental Management 6 (6): 485-492.
Puerto Rico: Yield
After four decades the productivity of the natural regeneration plot in the experiment was higher or equal to that of the plantation.

Kaeokamnerd, W. 1991. Travel Report to People's Republic of China. Mimeographed pp 60. UNDP/FAO/SIDA/RFD Project THA/86/016, Royal Forest Department, Bangkok.
China: Management
Mixtures of *Eucalyptus camaldulensis* and *E. exserta* with *Acacia auriculiformis* in alternate rows to improve soils and coppices noted.

Kageyama, P.Y., Biella, L.C. and Palermo, A. 1990. *Plantacoes mistas com especies nativas fins de protecao e reser vatorios.* Paper presented to 6th Congresso Florestal Brasileiro, Campos do Jordao, Sao Paolo, Mimeograph 11 p.
Brazil: Management
Analysis of one year old mixed plantations. Silvicultural performance, height growth, is correlated to ecological groups of secondary succession.

Kanowski, P.J. and Savill, P.S. with Adlard, P.G., Burley, J., Evans, J., Palmer, J.R., and Wood, P.J. 1990. Plantation forestry. World Bank Forestry Policy. Issues Paper. Oxford Forestry Institute.
General: Soils. Environmental, pests and diseases
Second rotation decline of the kind observed in South Australia can be avoided by appropriate silviculture and tree breeding.

Kawahara, T. and Yamamoto, K. 1986. (Studies on mixed stands of akamatsu (*Pinus densiflora*) and hinoki (*Chamaecyparis obtusa*) (III) Stem volume of mixed stands.) Journal of Japanese Forestry Society 68 (8): 327-332.
Japan: Yield
Hinoki height is equal in mixed and pure stands, diameter and tree volume greater in pure. Total stem volume is greater in mixed stands than pure stands of either species.

Kawahara, T., Sato, A., Takeuchi, I., Tadaki, Y. and Hatiya, K. (1981). Litter fall and its decomposition in a mixed stand of Japanese larch (*Larix leptolepis*) and hinoki (*Chamaecyparis obtusa*). Bulletin Forestry and Forest Products Research Institute, Japan. No.313: 79-91.
Japan: Soils
Leaf decomposition was faster for mixed leaves than for either species alone.

Keating, W.G. 1981. Utilization of mixed species through grouping and standards. Australian Forestry 43 (4): 233-244.
Australia: Management
The author recommends grouping of timbers into strength groups based on the requirements for structural materials to overcome the problem of

marketing mixed species. This requires good knowledge of the characteristics of each species and effective grading techniques.

Keeves, A. 1966. Some evidence of loss of productivity with successive rotations of *Pinus radiata* in the south east of South Australia. Australian Forestry 30; 51-63.
Australia: Yield
First rotation felled at 24.5 years after a fire, second rotation assessed at 9.5 years. Commonly a drop of 1 - 2 Site Quality classes, sometimes as much as 4 classes.

Kelty, M.J. 1989. Productivity of New England hemlock/hardwood stands as affected by species composition and canopy structure. Forest Ecology and Management 28: 237-257.
USA: Yield
Hemlock presence resulted in lower stocking of hardwoods in mixed stands (30%) as well as lower volume (20%) and 5 year increment (14%) of the hardwoods. Total stocking increased (65%) as well as volume (27%) and increment (18%). Silvicultural gains are better conditions for regeneration and less epicormics.

Kemp, R.H. 1992. The conservation of genetic resources in managed tropical forests. Unasylva 43 (169): 34 - 40.

Kenk, G.K. 1990a. The silviculture of mixed species stands in Germany. In Ecology of Mixed Stands of Trees. British Ecological Society and IUFRO Div S2.01 Symposium, Edinburgh.
Germany: Management
Clear objectives of mixtures, knowledge of sites and of growing rates of combining species are indispensable. The selection forest is often seen as an ideal, but its possibilities get over estimated. 672 mixed stand types identified.

Kenk, G.K. 1990b. Effects of air pollution on forest growth in southwestern Germany - hunting for a phantom? Proceedings Div.2 XIX IUFRO World Congress. Aug 1990, Montreal. p 388-395.
Germany: Yields, Disease
Comments on the yields of stands suffering crown decline in which yields may be higher than predicted. May be due to increased temperature, CO_2, rainfall or mineralization.

Kenward, R.E. 1990. Are tree species mixtures too good for grey squirrels? In Ecology of Mixed Stands of Trees. British Ecological Society and IUFRO Div S2.01 Symposium, Edinburgh.
UK: Wildlife
An analysis of the grey squirrel problem in forestry.

Kerr, G., Nixon, C.J. and Matthews, R.W. 1990. The silviculture and yield of mixed species stands: the UK experience. In Ecology of Mixed Stands of Trees. British Ecological Society and IUFRO Div S2.01 Symposium, Edinburgh.
UK: Management. Yield
It is believed that nurse crops increase profitability and flexibility in the lowlands. In the uplands benefits have been clearly demonstrated on certain soils. Mixing spruce with pine or larch is recommended on nutritionally deficient soils in the upland heaths.

Kio, P.R.O. 1976. What future for natural regeneration of tropical high forest? An appraisal with examples from Nigeria and Uganda. Commonwealth Forestry Review 55 (4): 309-318.
Nigeria: Economy. Management
It is argued that natural regeneration is more economic than plantations (*Gmelina* on a 40-year rotation), that includes an assumed 25% decline in yield in the second rotation.

Kolesnichenko, M.V. and Chumakov, V.V. 1973. Basis for selection of species for admixture in mixed plantations of Canadian poplar. Lesnoi Zhurnal 16 (5): 12-16.
USSR: Soils, nutrients
Betula verrucosa, Sambucus racemosa and *Ulmus pumila* var. *arborea* inhibited poplar growth. *Robinia pseudoacacia, Caragna arborescens, Lonicera tatarica, Alnus glutinosa, Cotinus coggyria* and *Fraxinus pennsylvanica* activated. It is suggested that inhibitor spp. should be included (10-20%) to promote a "response reaction" in the poplar.

Kon, I. 1973. Growth of *Cryptomeria japonica* in mixture with *Pinus elliottii* var *elliottii* on the Arraial Estate, Parana, Brazil. Floresta 4 (2): 30-33.
Brazil: Yield
A note on the performance of the species after three years.

Kormanik, P.P. 1979. Biological means of improving nutrient uptake in trees. In the Ecology of even-aged forest plantations. Ford, E.D., Malcolm, D.C. and Atterson, J. eds. Proceedings Div 1. IUFRO. Institute of Terrestrial Ecology, Cambridge.
General: Soils, nutrients
Reviews the N fixing role of micro-organisms and mycorrhizal fungi.

Kramer, F. 1925. *Het verjongingsonderzoek van sandelhout (Santalum album) op Java.* (Research on the regeneration of sandalwood (*Santalum album*) in Java.) Korte Meded. P.v.b.H. 10 and Tectona 18: 455-498. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 642.
Indonesia: Management
Santalum album was mixed with field crops and *Leucaena glauca.* Many seedlings died when unable to reach the roots of plants in the intermediate row. Low herbs around the seedlings helped. Once the roots reached the *Leucaena,* they developed well.

Krishnamurthy, K., Munegowda, M.K. and Rajagopal, D. 1990. Outbreak of Psyllid, *Heteropsylla cubana* Crawford on Leucaena and its outlook in alley cropping in India. In Leucaena Psyllid: Problems and Management. International Workshop, Bogor, Indonesia ed. Napompeth, B. and MacDicken, K.G. pp 17-24.
India: Pests
Describes distribution, damage and attempts at control of the insect.

Kunst, E.D. 1918. *Toelichtingen bie de excursie der houtvesters in de 2de en 5de Inspectie-afdeeling naar Karanggedeh op 21 December 1918.* (Explanations at the excursions of the forest district officers of the second and fifth inspection division to Karanggedeh on 21 December 1918.) In: *Boschwesen, Dienst van het, 1918. Notulen van de gecombieerde dienstvergadering der tweede en vijfde inspectieaafdeeling van het Boschwesen te Samarang op den 20 December 1918.* (Minutes of the combined service meeting of the second and fifth inspection division of the forest service in Samarang, 20 December 1918.) Unpublished. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 606.
Indonesia: Management
If fires are avoided, natural mixing species develop vigorously. Natural mixing is to be preferred to artificial.

Lahiri, A.K. 1987. A note on the prospects of *Tectona grandis* and *Xylia dolabriformis* mixtures in North Bengal. Indian Journal of Forestry 10 (3): 232-233.
India: Management
A line mixture of *Xylia dolabriformis* and *Tectona grandis.* 2x2 m spacing, 4 lines teak, 4 lines of *Xylia* and 4 lines of *Schima*

wallichii, Chukrasia tabularis, Michaelia champaca mixed. The last two are fire tender and tended to be eliminated. At 5 years mean height 6 m, dbh of fire tender spp. 5.1 cm, the rest 7-8 cm.

Lamb, A.F.A. 1969. Artificial regeneration within the humid lowland tropical forest. Commonwealth Forestry Review 48 (1): 41-53.
Nigeria: Management.
Nauclea diderrichii used in matrix with *Meliaceae, Lovoa trichilioides, Khaya ivorensis, Entandrophragma utile, E.cylindricum, E.angolense.* 5 *Nauclea* to 1 *Meliaceae.* 3.7 m spacing. *Nauclea* removed at age 12 to 15. *Meliaceae* harvested at 60 to 70 years. On Amazon infertile soils alternate rotations of shade tolerants is recommended.

Lamb, A.F.A. 1991. Personal communication.
Nigeria: Management
Lovoa too slow growing to keep up with the *Nauclea. Cedrela odorata* not attacked by *Hypsipyla* in Nigeria.

Lawton, R.M. 1991. Personal communication.

Leclerq, W.L., 1960. *Fomes annosus* and *Prunus serotina.* Ned. Bosb. Tijdschr. Vol 33 (2): 74-75.
The Netherlands: Environmental, pests and diseases
The possible danger of using *Prunus serotina* in combination with conifers is discussed.

Leslie, A.J. 1966. The problem of limited funds in tropical forestry. Commonwealth Forestry Review 45 (2): 156-159.
The tropics: Management. Economy
There is no case for allocating scarce funds for extensive silvicultural work in natural forests, achieving low economic returns, at the expense of intensive work in high yielding plantations.

Leslie, A.J. 1987. A second look at the economics of natural management systems in tropical mixed forests. Unasylva 155 (1): 47-58.
Tropics: Economics
In the management of tropical mixed forests the "non-revenue" benefits must not be overlooked. Economic prospects are largely governed by the rate of interest selected; the choice is subjective, but the appropriate rate is likely to be at the lower end of any plausible range.

Levy, G. 1982. *Estimation de l'utilité d'une introduction d'aulne glutineux en mélange a de jeunes plants d'épicéa commun sur sol a hydromorphie temporaire superficielle.* Annales des Sciences Forestieres 39 (1): 33-40.
France: Soils. Management
Two year data from a trial with alder mixed with Norway spruce (1:5) in troughs with pseudogley soils. Water table was 5 cm below surface. Evapotranspiration 19-34% greater than control. Lowering the water table improved rooting, N uptake, and spruce survival. In summer a lowered water table may have adverse effects on spruce.

Libby, W.J. 1982. What is the safe number of clones per plantation? In Resistance to Disease and Pests in Forest Trees. eds Heybroek, H.M., Stephan, B.R. and von Weissenberg, K. Proceedings Third International Workshop on the Genetics of Host Parasite Interactions in Forestry September 1980. Wageningen, Netherlands
pp 342-360.
Environmental: pests and diseases
Cross adaption of a short generation pest may be more likely among many clones than among a few unrelated clones. Monoclonal plantations are a good strategy, 2-3 clones possibly the worst strategy. A robust and perhaps optimum strategy is 7-25 clones.

Lohmander, P. 1990. *Flexibilitet - en ledstjaerna foer all skoglig planering.* Skogsfakta, inventering och ekonomi 23, Swedish University of Agricultural Sciences.
Sweden: Economy
Long-term predictions of timber prices and logging costs are impossible. So is the future impact of environmental changes. Therefore, maintenance flexibility is of vital importance. Mixed stands permit more flexibility. The most economic species can be encouraged in future thinnings.

Lowe, R.G. 1991 Personal communication.
Nigeria: Management

Lundgren, B. 1980. Plantation forestry in tropical countries - physical and biological potentials and risks. Rural Development Studies 8. Swedish University of Agricultural Sciences, International Rural Development Centre, Uppsala, Sweden.
The tropics: Soils
Argues that plantation forestry in the tropics should be treated much more as a short term crop, comparable to an agricultural crop, and that soil and site management has not been given adequate attention.

MacGregor, W.D. 1934. Silviculture of the mixed deciduous forests of Nigeria with special reference to the south-western provinces. Oxford Forest Memoirs 18. Oxford Forestry Institute (UK).
Nigeria: Management
Primarily concerned with natural forests, but the success of plantation mixtures and enrichment planting is commented on.

McColl, J.G. and Edmonds, R.L. 1983. Symbiotic nitrogen fixation by *Daviesia mimosoides* under Eucalyptus. In: IUFRO Symposium on Forest Site and Continuous Productivity, Seattle, Washington, August 1982. General Technical Report, Pacific Northwest Forest and Range Experiment Station, US Dept. of Agriculture Forest Service (1983), No. PNW-163, pp. 122-129.
Australia: Soils
On red earth kraznozems derived from highly weathered Ordovician sediments *E.dives* and *E.dalrympleana* grow on exposed ridges with an understorey of *D. mimosoides,* fixing 4.5-7 kg/ha/yr. The pattern of N fixing is examined. N fixing rate constant at normal soil tension, a drop when plants reach wilting point. Increased N fixing up to -.01 then sudden drop (anaerobic conditions).

McIlroy, J.C. 1978. The effects of forestry practice on wildlife in Australia. A review. Australian Forestry 41 (2): 78-94.
Australia: Wildlife
The general effect of forestry practices is to reset or initiate succession of plant and animal communities. Management plans cannot wholly replace reserves and national parks.

McKinnell, F.H. 1990. Status of management and silviculture research on Sandalwood in Western Australia and Indonesia. In Proceedings of the Symposium on Sandalwood in the Pacific, April 1990, Honolulu, Hawaii. US Department of Agriculture, Forest Service, General Technical Report PSW-122. p 19-25.
Australia, Indonesia: Management
A general description of Sandalwood management and research in Western Australia and Indonesia.

Maheut, J. and Dommergues, Y. 1959. *La fixation par le reboisement de dunes de la presqu'île de Cap Vert et l'évolution des sols.* (Fixation of the Cape Verde Peninsula sand hills by reafforestation.) Bois et Forêts des Tropiques No. 63: 3-16.

Senegal: Soils
Casuarina equisetifolia raises biological activity. Therefore it is considered a suitable species for reafforestation sand hill soils. Crop rotation may prove necessary.

Magundikoro, I.A. and Depari, K.S. 1958. (Insect and fungus attacks in the pine forest of northern Sumatra.) Rimba Indonesia 10-12: 417-452.
Indonesia: Environmental, pests and diseases
Mixing with deciduous species is among the measures recommended to lessen the insect attacks on *Pinus merkusii* in the area.

Maheut, J. and Dommergues, Y. 1960. *Les teckeraies de Casamance - Capacité de production des peuplement caractéristiques biologiques et maintien du potentiel productif des sols.* (Teak plantations of Casamance - Biological characteristics and maintenance of the productive potential of soils.) Bois et Forêts de Tropiques 70: 25-42.
Senegal: Soils. Yield
There is reason to fear a future decline in the yield of teak plantations in Casamance. Mixing is among the preventive measures suggested.

Malcolm, D.C. 1979. The future development of even-aged plantations: silvicultural implications. In: the ecology of even-aged forest plantations. Proceedings of the meeting of Division I, IUFRO, Edinburgh, Sept. 1978. Institute of Terrestrial Ecology, Cambridge (UK), 1979. pp 481-504.
UK: Ecology. Management

Malcolm, D.C. and Titus, B.D. 1983. Decomposing litter as a source of nutrients for second rotation Sitka Spruce established on peaty gley soils. In: IUFRO Symposium on Forest Site and Continuous Productivity, Seattle, Washington, August 1982. General Technical Report, Pacific Northwest Forest and Range Experiment Station, US Dept. of Agriculture Forest Service (1983), No. PNW-163, pp 138-145.
UK: Soils
Leaving brash after felling on gley soils promoted a high release of nutrients and weed growth. Without brash there was a tendency for nutrients to be lost in run off.

Malcolm, D.C., Hooker, J.E. and Wheeler, C.T. 1985. *Frankia* symbiosis as a source of nitrogen in forestry: a case study of symbiotic nitrogen-fixation in a mixed *Picea-Alnus* plantation in Scotland. In Symbiosis and Plant Nutrition. Proceedings of the Royal Society of Edinburgh 85 (3/4): 263-282.
UK: Soils
In a 16-year-old plantation on moderately fertile clay a line mixture of *Alnus rubra* did not improve growth of *P.sitchensis* as against a pure spruce plantation. The presence of alder increased upper soil N status by 585 kg/ha.

Malcolm, D.C., Campbell, J.M. and Morgan, J.L. 1990. Synergism in mixed species stands on oligotrophic sites in Scotland. In Ecology of Mixed Species Stands of Trees. British Ecological Society and IUFRO Div 2.01 Symposium, Edinburgh.
UK: Soils
Beneficial effects of Pine and Larch mixtures with Spruce start to appear about age 6 - 8. Differences in rooting intensities and patterns together with increased N mineralisation rates in organic surface soils appear to be sufficient to account for the enhanced growth in mixtures.

Mallet, B. 1988. *Note sur la croissance de Khaya senegalensis en plantations en zone de forêt semi-décidue en Côte d'Ivoire.* CTFT (unpublished).
Côte d'Ivoire: Management

Khaya senegalensis seems to grow best in openings, although *Hypsipyla robusta* poses problems. Stem form is better when mixed with *Leucaena leucocephala* or *Cedrela odorata,* attacks of *H.robusta* being delayed.

Mangoendihardjo, S., Wagiman, F.X., Suthoni, A. and Subyanto. 1990. Economic impact of Leucaena Psyllid infection on estate crops and teak forest plantation. In Leucaena Psyllid: Problems and Management. Workshop in Bogor, Indonesia. F/FRED Coordinating Unit, Bangkok. pp 184-188.
Indonesia: Pests
Gives details of areas infected and financial loss involved.

Manil, G. 1971. (The problem of maintaining the fertility of the soils under pure conifer plantations.) Bull. Soc. For. Belg. 78 (5): 217-250.
Belgium: Soils
A review of the effect of conifer plantations on soils and ecosystems.

Martin, B., Laplace, P. and Quillet, G. 1989. *L'UAIC Afocel-Armef Informations Forêt.* No.2 - 1989. Pointe-Noire, Congo.
Congo: Management
Description of clonal eucalypt plantations. Spatial mixtures achieved by mixing clones, 42 clones used but on 50% of the area only 5 were used. Mixtures were also achieved over time by succession. Advantages include large genetic base and uniformity of output.

Martin, B. 1991. *Les croisements controlés industriels: appui majeur à la voie clonale. Nouvelle stratégie pour les plantations forestières intensives.* Paper, Theme 13, 10th World Forestry Congress, Paris, 1991. Proceedings, Vol.5: 43-49.
Congo: Clonal forestry

Mathew, G. 1990. Cossid pests of teak in the Asian Region and the possibilities of their control. In Pests and Diseases of Forest Plantations in the Asia-Pacific Region. FAO, Regional Office for Asia and the Pacific, Bangkok. pp 204-213.
Asia: Pests
A review of these pests and their control.

Matziris, D. 1991. Selection and plantation of species and provenances in relation to sites and objectives. Paper, Theme 13.2, 10th World Forestry Congress, Paris, 1991. Proceedings, Vol.5: 77-84.
Includes a recommendation for the use of mixtures.

Merlin, M. and Van Ravenswaay, D. 1990. The history of human impact on the genus *Santalum* in Hawaii. In Proceedings of the Symposium on Sandalwood in the Pacific, April 1990, Honolulu, Hawaii. US Dept. of Agriculture Forest Service, General Technical Report PSW-122.
pp 46-60.
Hawaii: Management, exploitation and conservation
A brief survey.

Mielikainen, K. 1985. The structure and development of pine and spruce stands with birch mixture. In: Broadleaves in Boreal Silviculture - An Obstacle or an Asset? (Hagglund, B. and Petterson G. eds). Swedish University of Agricultural Sciences, Department of Silviculture, Report 14: 189-206.
Finland: Yield
Admixture of *Betula pendula*, 25 to 50%, enhances yield of spruce at all ages. Mixed with pine, it enhances yields only if removed early, 20-30 years. Mixed with pine it depresses sawtimber yields. *Betula pubescens* does not enhance spruce growth, but can act as filler in gappy plantations.

Miller, P.R. and Eiderman, M.J. (eds). 1977. Photochemical oxidant air pollutant effects on a mixed conifer forest ecosystem.

EPA 600/3-77-104. USEPA, Corvallis, Oregon. pp 338.
Environment: Pollution

Moffat, A.J. and Boswell, R.C. 1990. Effect of tree species and species mixtures on soil properties at Gisburn forest, Yorkshire. Soil Use and Management 6 (1): 46-51.
UK: Soils
32 year old mixture experiment with Scots pine, Norway spruce, oak, alder and grass control. The soil under conifers and alder was slightly more acid than under oak and grass. pH decline on all plots. Conifers had thicker F and H, but thinner A, horizons. Conifers and alder may have retarded formation of an iron deficient B horizon.

Mohns, B., Applegate, G.B. and Gilmour, D.A. 1988. Biomass and productivity estimations for community forest management: a case study from the hills of Nepal - II. Dry matter production in mixed young stands of Chir pine (*Pinus roxburghii)* and broad leaved species. Biomass 17: 165-184
Nepal: Yields
Standing biomass varied from 15t/ha (7.74 pine, 7.26 broadleaves) on southern slope ridge to 41.77 (29.73 pine, 12.04 broadleaves) on northern slope. Annual dry matter production from 4.50t/ha/yr (2.27 pine, 2.23 broadleaves) to 10.82 (6.74 pine, 4.08 broadleaves).

Mooney, J.W.C., 1962. The tropical shelterwood system in the high forest of Ghana. Commonwealth Forestry Review 41 (3): 205-208.
Ghana: Management
Discusses the need for clear objectives and management of incompatible species. Most valuable timbers are slow growing shade bearers. Higher volumes can be achieved with light demanders. Higher utilisation in production for the local market than for export. TSS considered unsuitable for production of "quality" species.

Mopri Bilan 1987. *Essais comportement Cedrela odorata*.
CTFT (unpublished).
Côte d'Ivoire: Yield
Productivity of pure stands of *Cedrela odorata* was found to be higher than stands of *C.odorata* and *Terminalia ivorensis* mixed.

Moraes **de Jesus, R. and Brouard, J.S. 1989.** *Eucalyptus-Leucaena* mixture experiment. I. Growth and yield. International Tree Crops Journal 5: 257-269.
Brazil: Yield
A trial with *E. urophylla* and two varieties of *L. leucocephala*. At age 7 eucalyptus survival varied from 75% (control) to 50% mixture). *Leucaena* survival was 95%. Eucalyptus yield in control was greater than in mixed plots, in turn greater than the *Leucaena*. Inorganic fertilizer may have reduced the N fixing of the *Leucaena*.

Morris, A.R. 1986 Soil Fertility and Long term Productivity of *Pinus patula* in Swaziland. Unpublished Thesis for PhD, Reading University (UK). pp 398.
Swaziland: Soils
Estimates of nutrient removal, nutrient content of the mature stand, soil nutrient content and nutrient removal in harvested logs.

Moss, D. 1979. Even-aged plantations as a habitat for birds. In: The ecology of even-aged forest plantations. Proceedings of the meeting of Division I, IUFRO, Edinburgh, Sept. 1978. Institute of Terrestrial Ecology, Cambridge (UK), 1979.
UK: Wildlife
Wildlife diversity increases at the boundaries of two habitats. Decline of a species may be due to the removal of its food supply rather than

the presence of trees (e.g. ravens and sheep on moorlands). Diversity of structure (all ages) as important as diversity of species.

Muir, W.D. 1970. The problem of maintaining site fertility with successive croppings. Australian Journal of Science 32 (8): 316-324
General: Soils
Decline in productivity in second rotation crops appears to be confined to soils of low natural fertility.

Murray, M.D. and Miller, R.E. 1986. Early survival and growth of planted Douglas-fir with red alder in four mixed regimes. Pacific North West Research Station, US Dept. of Agriculture Forest Service. pp 13.
USA: Management
Retaining 1250 red alder/ha to 6-8 years had no adverse effect on Douglas fir in Cascade Range.

Murray, M.D. and Leonard, P.C. 1990. Growth of trees and stand structure in mixed stands of Pacific silver fir and western hemlock. US Dept. of Agriculture Forest Service Research Paper PNW-RP-431. pp 12.
USA: Management
An analysis of six hemlock/silver fir stands. Hemlock (*Tsuga heterophylla*) has faster initial height growth but silver fir (*Abies amabilis*) after about 35 years has faster growth. Therefore fir should not be discriminated against in early thinnings.

Muttiah, S. 1965. A comparison of three repeated inventories of Sundapola mixed selection working circle and future management. Ceylon Forester 7(1/2): 3-35.
Sri Lanka: Management
Swietenia macrophylla mixed with *Tectona grandis* and *Artocarpus integrifolius*. Age unknown. *S.macrophylla* 59 to 84% of crop (by stem number), *T. grandis* 2 to 15% and *A.integrifolius* 8 to 19%. Volume 94 to 155 m^3/ha (dbh up to 58 cm), but trees over 78 cm felled 1955-1960. Profuse mahogany regeneration. Proposal to treat as selection forest to achieve an all age structure.

Muttiah, S. 1991. Personal communication.
Sri Lanka: Management
Sundapola plantations established circa 1901. The potential for conversion to uneven-aged (pure) plantation was recognised in the early 1950s. But Mahogany could not have been established without the mixture. Probably inadvisable to go to pure plantation. Exploitation carried out with extreme care.

Neil, P.E. 1990. Growing Sandalwood in Nepal - Potential silvicultural methods and research priorities. In Proceedings of the Symposium on Sandalwood in the Pacific, April 1990, Honolulu, Hawaii. US Department of Agriculture, Forest Service, General Technical Report PSW-122. pp 72-75.
Nepal, India: Management
A brief description of silvicultural management proposals.

Nelson, T.C. 1964-65. Growth models for stands of mixed species composition. Proc. Soc. Amer. For. 1964, 1965, pp. 229-231.
USA: Yield
Based on a simplified theory, a growth model for mixed stands is proposed.

Ng, F.S.P. 1991 Personal communication.
Malaysia: Management
The Kepong plantings were established as demonstration plots under *Albizia falcataria*, which was removed. Dipterocarps were successful, but eucalyptus a failure. Understorey species have regenerated natural-

ly. In 30 years a mixed forest had been created. After 60 years used as a recreational area.

Ng, F.S.P, Zulkifly bin Haji Mokhtar, Ahmad Abdul Ghani bin Abdul Aziz 1982. *Leucana leucocephala* as a tall cover crop for sawlog plantations. In: *Leucaena* Research in the Asian-Pacific region, Singapore 1982, pp 113-118. IDRC, Canada.
Malaysia: Management, cover crops
Leucaena has been used as a tall cover crop together with *Tectona grandis* and *Araucaria hunsteinii*. It shows promise in suppressing *Imperata*, less so in suppressing *Pueraria* and *Centrosema*.

Nielsen, P. 1991. (Forest Reseach Branch, Queensland) Personal communication.

Nogueira, J.C.B. 1977. *Reflorestamento heterogeneo com essencias indigenas*. Boletim Tecnico, Instituto Florestal, Sao Paulo 24: 1-77.
Brazil: Management
A description of the reforestation of a small area of degraded riparian forest. After 22 years a vigorous semi-deciduous tropical forest had been developed.

Nordstroem, L. 1964. *Ek och gran.*(Oak and spruce), Skogen 21.
Sweden: Management
A silvicultural regime for regenerating oak in group mixture with spruce is presented. The aim of the regime is a pure stand of high quality oaks.

Novais, R.F. de and Poggiani, F. 1983. *Deposicao de folhas e nutrientes em plantacoes florestais puras e concoriadas de Pinus e Liquidambar.* (Leaf fall and nutrient return in pure and mixed plantations of *Pinus* and *Liquidambar*.) IPEF No. 23: 57-59.
Brazil: Soils
Leaf heterogeneity on the floor of the mixed stand appears to increase litter decomposition and to improve nutrient cycling.

Nwoboshi, L.C. 1983. Potential impacts of some harvesting options on nutrient budgets of a *Gmelina* pulpwood plantation ecosystem in Nigeria. In: IUFRO Symposium on Forest Site and Continuous Productivity, Seattle, Washington, August 1982. General Technical Report, Pacific Northwest Forest and Range Experiment Station, US Dept. of Agriculture Forest Service (1983), No. PNW-163.
Nigeria: Soils. Management
Data on the nutrient status of a 10 year old plantation of *Gmelina arborea*. Soil and erosion data are also presented.

Odendaal, P.B. and Bigalke, R.C. 1979. Habitat selection by bushbuck in a disturbed environment. South African Forestry Journal 108: 39-41.
South Africa: Wildlife
Five animals radio tracked. Indigenous broadleaved forest met their total requirements. Clearfelled areas preferred at night, and dense *Pinus radiata* and *P.elliottii* plantations at day. Lowest preference was for *Eucalyptus diversicolor* plantations.

Okafor, J.C. 1977. Development of forest tree crops for food supplies in Nigeria. Forest Ecology and Management 1 (3): 235-247.
Nigeria: Social
The importance of tree fruits is stressed. Their silvicultural requirements are unknown.

Oliver, C.D. 1980. Even-aged development of mixed-species stands. Journal of Forestry 78: 201-203.
North America: Management

Stratified forests need not be unevenaged. Certain mixtures e.g. Douglas fir/western hemlock may have higher basal area than pure stands of either species.

Palmer, J.R. 1986. Jari: Lessons for land managers in the tropics. Bois et Forêts des Tropiques 212 (2): 16-27.
Brazil: Management
Site preparation damaging to the soil. Lack of site matching for *Gmelina* (only. 25% of area suitable).

Pandey, D. 1992. Assessment of tropical forest plantation resource. Department of Forest Survey, Swedish University of Agricultural Sciences (unpublished).

Paschke, M.W., Jeffrey, O.D and David, M.B. 1989. Soil nitrogen minerali zation in plantations of *Juglans regia* interplanted with actinorhizal *Elaeagnus umbellata* or *Alnus glutinosa*. Plant and Soil 118: 33-42.
USA: Soils. Yield
Examination of mineralised N under 18 year old walnut planted pure and interplanted 3:1 with autumn olive and alder. There was a marked increase in mineralised N under olive, less under alder. Up to 18 kg/ha/year = 13.5% of total N pool under olive and as low as 52 kg/ha/year in control. Walnut growth correlated with N mineralisation.

Peace, T.R. 1957. Approach and perspective in forest pathology. Forestry 30: 47-56.
General: Disease
A review of the problem. "Broad assumptions lead to false simplifications. We know regrettably little about health and disease in trees."

Peck, K.M. 1990. Habitat preferences of birds: the importance of diversity in woodlands. In Ecology of Mixed Species Stands of Trees. British Ecological Society and IUFRO Div 2.01 Symposium, Edinburgh.
UK: Wildlife
Number of species (passerines) correlated with tree species richness and diversity. Tree preferences change seasonally and were attributed to changes in food availability.

Perera, W.H. 1962. The development of forest plantations in Ceylon since the 17th century. Ceylon Forester 5 (3): 142-151.
Sri Lanka: Management
Swietenia macrophylla under 3 year old *Artocarpus heterophyllus* 1890 onwards. Also *S.macrophylla* and *Cedrela mexicana* enrichment planting and *S.macrophylla* under 2nd generation teak.

Perry, D.A. 1979. Variation between and within tree species. In Ecology of Even-aged Plantations. Ford, E.D., Malcolm, D.C. and Atterson, J. (eds). pp 71-98.
General: Ecology

Perry, D.A. and Maghembe, J. 1989. Ecosystem concepts and current trends in forest management: time for reappraisal. Forest Ecology and Management 26: 123-140.
General: Environmental. Economy
Current economic criteria do not address a number of important factors, e.g. sustainability and diversity.

Perry, D.A., Bell, T. and Amaranthus, M.P. 1990. Mycorrhizal fungi in mixed-species forests and other tales of positive feedback, redundancy and stability. In Ecology of Mixed Species Stands of Trees. British Ecological Society and IUFRO Div 2.01 Symposium, Edinburgh.
USA: Soils

The effect of mycorrhizal fungi on competition between plants of different species show that they convert a negative interaction into one that is either neutral or positive (increases yield). They physically link trees with their hyphae, through which carbon and nutrients probably pass.

Phillips, D.R. and Abercrombie, J.A. 1987. Pine-hardwood mixtures - A new concept in regeneration. Southern Journal of Applied Forestry. 11 (4): 192-197.
USA: Management
A regime is proposed, where natural regeneration of hardwoods is retained together with pine seedlings.

Pierlot, R. 1955. *Le reboisement en placeaux espacés. Bulletin d'Information de l'INEAC* 4 (5): 325-338.
Zaire: Management
A regeneration system, planting in spaced dense groups, is presented.

Poole, B. 1989. Forest health issues in south-east Asia. New Zealand Journal of Forest Science 19 (2/3): 159-162
Asia: Environmental, pests and diseases
A review of important insect pests in south-east Asia.

Poore, M.D., Burgess, P.F., Palmer, J.R., Reitenbergen, S. and Synnott, T.J. 1989. No Timber without Trees. Earthscan Publications Ltd., London WC1H 0DD. 252 pp.
General: Management
An overview of mainly natural forest policies.

Prasad, K.G., Singh, S.B., Gupta, G.N. and George, M. 1985. Studies in changes in soil properties under different vegetations. Indian Forester 111 (10): 794-7911.
India: Soils
After 40 years organic carbon had decreased in the top 18 cm of the soil. Natural forest: mixed plantation: teak plantation 1.7:-1.5:0.8%. P_2O_5 13:17:10 ppm. Total Mg 1.6:1.5:0.9 but exchangeable Mg increased under teak. Soil considered less fertile under Teak.

Pryor, S.N. and Savill, P.S. 1986. Silvicultural systems for broadleaved woodland in Britain. Oxford Forestry Institute (UK) Occasional Paper 32.
UK: Management
Greater production from selection forests unproven, but claim for greater value more sustainable.

Queensland 1990. Annual Report for 1989. Queensland Forest Department.
Australia: Management
Includes a statement of areas of plantations by species.

Rackham, O. 1990. Mixtures, mosaics and clones: the distribution of trees within European woods. In: Ecology of Mixed Species Stands of Trees. British Ecological Society and IUFRO Div 2.01 Symposium, Edinburgh.
Europe: Environmental
Pure natural stands are often in extreme environments, *Pinus mugo, P. cembra* and *Alnus viridis* at high elevations, *Betula* in the far north, *Cupressus sempervirens* on south-facing limestone in Crete, *Quercus petraea* in the Atlantic climate of west Britain, *Alnus glutinosa* in peaty valleys, *Quercus* and *Fagus* in browsed areas.

Radwan, M.A. and DeBell, D.S. 1988. Nutrient relations in coppiced black cottonwood and red alder. Plant and Soil 106 (2): 171-177.
USA: Management
Mixed culture of *Populus trichocarpa* and *Alnus rubra* appears promising because of the increased growth of the poplar.

Rai, S.N. 1990. Status and cultivation of Sandalwood in India. In Proceedings of the Symposium on Sandalwood in the Pacific, April 1990, Honolulu, Hawaii. US Department of Agriculture, Forest Service, General Technical Report PSW-122. pp 66-71.
India: Management, Ecology, Yields, Marketing
A brief account of Sandalwood cultivation.

Ram Prasad 1988. Sal plantation on bauxite mined out site of Madhya Pradesh. Journal of Tropical Forestry 4 (1): 68-73.
India: Soils
Some methods of revegetating a mined out site were tried. One of the methods was sal (*Shorea robusta*) mixed with *Grevillea robusta, Eucalyptus camaldulensis, Toona ciliata* and *Pinus kesiya*.

Ram Prasad and Camire, C. 1988. Afforestation of dolomite mine overburdens in Madhya Pradesh. Journal of Tropical Forestry 3 (2): 124-131.
India: Management. Yield
Acacia auriculiformis, A. campylacantha, Gmelina arborea, Eucalyptus hybrid, and Pongamia pinnata grown with bamboo had rather better height and diameter growth and survival than when grown without. *Albizia procera* had slightly worse growth.

Ratcliffe, P.R. and Petty, S.J. 1988. The management of commercial forests for wildlife. Nat. Environ. Res. Council. Inst. Terrestrial Ecology (U.K.) Symposium Proceedings: 17: 177-187.

Raunio, A.L. 1991. Personal Communication.
Ethiopia: Management
Grevillea robusta planted into a coppiced *Eucalyptus grandis* stand of low stocking - showing promise. *Pinus radiata* being planted as a 25% mixture with *Pinus patula* or *Cupressus lusitanica*. Both line mixtures. *Grevillea* is not browsed by duiker.

Reddell, P. 1990. Increasing productivity in plantings of *Casuarina* by inoculation with *Frankia*. In Advances in *Casuarina* Research and Utilization. Desert Development Center, American University in Cairo, Box 2511, Cairo, Egypt.
Queensland, Zimbabwe: Soils
Inoculation with *Frankia* can result in up to 100% increase in wood production in 4 year old trees of *C.cunninghamiana*. Omission of P from nutrients applied can reduce growth by 75%.

Reddell, P., Rosbrook, P.A., Bowen, G.D. and Gwaze, D. 1988. Growth responses in *Casuarina cunninghamiana* plantings to inoculation with *Frankia*. Plant and Soil 108: 79-86.
Australia, Zimbabwe: Soils
One *Frankia* strain increased height growth by 200% at age 14 months in Zimbabwe. Wood production increases up to 150% at age 45 months were noted in Queensland. Application of P increased wood production by up to 250% over control.

Reese, K.P. and Ratti, J.T. 1988. Edge effect: a concept under scrutiny. Trans. 53rd. North American Wildlife and Natural Resources Conference. pp 123 - 136.

Rehmani, A.R. 1989. The great Indian bustard. Final Report. Bombay Natural History Society, India.

Rennie, P.J. 1962. Some long-term effects of tree growth on soil productivity. Commonwealth Forestry Review 41 (3): 209-213.
UK: Soils
Comparison of soils under 70 year old hardwood and conifer on *Calluna* moorland with impoverished soils. Conifers increased porosity in humus layer more than hardwoods. Both impoverished mineral soils below 30 cm,

conifers more than hardwoods. Conifers reduced pH from 3.3 to 3.1, hardwoods increased pH to 3.5.

Robinson, J.B.D. 1967. The effect of exotic softwood crops on the chemical fertility of a tropical soil. East African Agricultural and Forestry Journal 33: 175-189.
Kenya: Soils
Comparison of indigenous forest, first and second rotation conifer and hardwood plantation following conifer.

Robinson, J.B.D, Hosegood, P.H. and Dyson, W.G. 1966. Note on a preliminary study of the effects of an East African softwood crop on the physical and chemical condition of a tropical soil. Commonwealth Forestry Review 45 (4): 359-365
Kenya: Soils
Soils examined under a 16 year old *Cupressus lusitanica* plantation standing at 420/ha and a neighbouring secondary forest.

Robinson, R.K. 1973. Mycorrhizas and "second rotation decline" in *Pinus patula* in Swaziland. South African Forestry Journal 84: 16-19
Swaziland: Soils
A positive correlation between the mean number of mycorrhizal roots, the degree of infection and crop vigour in each of two rotations. Lack of vigour may be a consequence of low biological activity as evinced by a build up of litter, absence of earthworms and lack of mycorrhiza.

Rodgers, W.A. 1992. Managing forests for biodiversity in India: a review of concepts and practices. Manuscript. Wildlife Institute of India, Dehra Dun. 75 pp.

Ryan, E.A. and Alexander, I.J. 1990. Mycorrhizal aspects of improved Sitka spruce growth in mixed stands. In: Ecology of Mixed Species Stands of Trees. British Ecological Society and IUFRO Div 2.01 Symposium, Edinburgh.
UK: Soils
Evidence given that *Suillus variagatus,* a mycorrhizal associate of *Pinus sylvestris* but not of *Picea sitchensis,* occurs in mixed plantations and may be able to degrade protein rapidly leaving 87% of the protein degradation products in solution, which may be available for uptake by the Sitka spruce.

Ryan, P.A. 1985. Hoop pine second rotation growth and nutrition. Paper presented to Second Rotation esyablishment: Problems, Possible Solutions and Identification of Research Needs Conference. Topic 2.2. Gympie, Queensland.
Australia: Yield. Management

Salwasser, H. 1985. Integrating wildlife into the managed forest. In: A Symposium on Forestry and Wildlife Management in Canada. Forestry Chronicle, 146 - 149.

Salwasser, H. 1990. Sustainability as a conservation paradigm. Cons. Biology 4 (3): 213 - 215.

Samraj, P.,Chinnamani, S. and Haldorai, B. 1977. Natural versus man-made forest in the Nilgiris with special reference to run-off, soil loss and productivity. Indian Forester 103: 460-465.
India: Soils. Yield
Run-off under *Eucalyptus globulus* and *Acacia mearnsii* was less than under natural forest, but more than protected grass plots and *Cytisus scoparius* plots. Yields of eucalyptus and wattle mixed, 700 stems/ha, 482 m^3/ha at age 10 as against 322 m^3 for Eucalyptus, 2500 stems/ha, and 125 m^3 for wattle, 1600 stems/ha, in pure plantations.

Sands, R. 1983. Physical changes to sandy soils planted to radiata pine. In: IUFRO Symposium on Forest Site and Continuous Productivity. p 146-152.
Australia: Soils
Examines the correlation between root growth and soil strength. Maintenance of soil organic matter is critical to productivity, both in increasing field capacity, soil N and total CEC.

Savill, P.S. and Evans, J. 1986. Plantation silviculture in temperate regions with special reference to the British Isles. Clarendon Press, Oxford.
Temperate region: Textbook
Due to economic advantages, plantation forestry is dominated by pure evenaged plantations. Instances where mixtures may be suitable are discussed.

Schlesinger, R.C and Williams, R.D. 1984. Growth response of black walnut to interplanted trees. Forestry Ecology and Management 9 (3): 235-243.
USA: Yield
At 13 years *Elaeagnus, Robinia, Alnus glutinosa* admixtures increased black walnut dbh at some locations (but not all). *E. umbellata* gave 56 - 351% increase in 4 out of 5 locations in Illinois, Missouri and Indiana. All species resulted in a 100% increase on an upland site.

Schubert, T.H. 1985. Preliminary results of Eucalyptus/legume mixtures in Hawaii. Nitrogen Fixing Tree Research Reports 3: 65-66.
Hawaii: Yield
Summary of *Eucalyptus/Albizia/Acacia* mixtures reported by Debell et al. Notes tests on proportions of each species used in mixture. In 50:50 and 66:34 *Eucalyptus: Albizia* mixtures, Eucalyptus dbh 6% to 15% greater than mixtures with higher proportions of Eucalyptus, but no information given on eucalyptus standing volumes.

Schutz, C.J. 1982. Monitoring the long-term effects of management practices on site productivity in South African forestry. South African Forestry Journal 120: 3-6.
South Africa: Management, Soils
No evidence of productivity decline attributable to management practices. There may eventually be problems of litter build up on poor sites under intensively managed stands.

Schutz, J.P. 1989. *Zum problem in Mischbestanden.* Schweiz. Z. Forstwesen 140 (12): 1069-1083.
Switzerland: Yield
Mixtures of spruce and beech are claimed to grow better than pure stands of either species.

Schutz, J.P. 1990. *Die waldbaulichen Moeglichkeiten und Grenzen von Mischbestockungen.* (Silvicultural possibilities and limits of mixed forests.) IUFRO World Congress, Montreal.
Switzerland: Management
Natural trends towards diversity should be promoted.

Serrano, R.C., Villanueva, T.R. and Sims, B.D. 1976. Surface run-off and sedimentation under *Albizia falcataria, Anthocephalus chinensis* and mixed secondary stands. Pterocarpus 2 (1): 35-46.
Philippines: Soils
Pure stands of *A. falcataria* gave by far the best protective cover.

Shainsky, L.J. and Radosevich, S.R. 1988. Douglas fir and red alder competition in mixed and monoculture stands. Vegetation Competition and Responses. Proceedings 3rd Annual Vegetation Management Workshop. Vancouver B.C., Canadian Forest Service. pp 2.
North America: Environmental

Interactions of the two species planted at 1 to 16 trees/m^2 are examined. Douglas fir at these densities reduced leaf area of alder as Douglas fir densities increased, but growth parameters of both species were primarily affected by alder densities.

Singh, A.K. and Totey, N.G. 1985. Physico-chemical properties of bhata soils of Raipur (Madhya Pradesh) as affected by plantations of different species. Journal of Tropical Forestry 1 (1): 61-69.
India: Soils
Plantation soils are examined, *Tectona grandis, Eucalyptus hybrid, Emblica officinalis* and "miscellaneuos". CEC, exchangeable cations and organic matter are higher under miscellaneous plantations, but stockings and growth are poor. The extent to which the soil effects can be attributed to the tree cover is debatable.

Singh, A.K., Arun Prasad, Khatri, P.K. and Balvinder Singh 1987. Physico-chemical properties of soils developed over gneissic rocks under different forest covers in Nagri range of South Raipur (Madhya Pradesh). Journal of Tropical Forestry 3(1): 37-47.
India: Soils
An examination of four forest covers, teak, sal, miscellaneous with sal and miscellaneous without sal.

Singh, S.B., Nath, S., Pal, D.K. and Banerjee, S.K. 1985 Changes in soil properties under different plantations of the Darjeeling forest Division. Indian Forester 111 (2): 90-98.
India: Soils
Mixed vegetation reflected the best soil properties.

Singh, S.P. and Sharma, R.S. 1983. Permanent sample plots in stands of mixed species. Indian Forester 109(7): 449-457.
India: Yields
A high proportion of *Trewia nudiflora, Toona ciliata* and *Bombax ceiba* resulted in larger volumes.

Siregar et al. 1986. Growth of *Swietenia macrophylla* and intercropped *Leucaena leucocephala* in the residual forest of *Melaleuca leucadendron.* Leucaena Research Report 7: 82.
Indonesia: Yield
The poor results may be due to allelopathy of *Melaleuca leucadendron,* drought stress or sulphur deficiency.

Smelyanetz, V.P., Lopatina, N.V. and Lomakin, M.D. 1981. Forest resistance to insect pests in relation to plant population patterns. Zeitschrift fuer angewandte Entomologie 92: (3): 217-244.
USSR: Environmental, pests and diseases
It is possible to use *Pinus sylvestris* as a diversionary plant within cultures of *Pinus pallasiana.*

Smith, D.M. 1962. The practice of silviculture. John Wiley and Sons, 7th edition.
Textbook: Management
Stratified mixtures should be used if intimate mixtures are to be maintained in plantations. It is almost impossible to find species that will form single canopied mixtures.

Smith, I.W., Marks, G.C, Featherston, G.R. and Geary, P.W. 1989. Effects of interplanted wattles on the establishment of eucalypts planted on forest sites affected by *Phytophthora cinnamoni.* Australian Forester 52 (2): 74-81.
Australia: Environmental, pests and diseases. Yield
No effects of the wattles on *P. cinnamoni* could be detected. Eucalypts seemed to respond well in growth to the interplanted wattles.

Soares, R.V. 1991. Ecological and economic consequences of forest fire: the Brazilian example. Theme 5.3, 10th World Forestry Congress, Paris, 1991. Proceedings Vol.2: 471-480.
Brazil: Fire

Solomon Islands 1988a. Notes on the use of mixtures and nurse crops in the establishment of plantations of high value spp. Forestry Note 30 7/88, Forest Department.

Solomon Islands 1988b. The status of *Securinega flexuosa* Muell. Arg. Forest Research Note 46 14/88, Forest Department.
Solomon Islands: Management
Swietenia macrophylla planted with *Securinega flexuosa, S.samoana, Leucaena leucocephala, Terminalia calamansanai, Schleinitschia novo-guinensis, Glyricidia sepium* to overcome *Hypsipylla* shoot borer. Spacing 3x4m or 3x5m. *S.flexuosa* most promising.

Soule, M.E. Ed. 1986. Conservation biology: science of scarcity and diversity. Sinauer Associates, Sunderland, Mass. U.S.A.

Spears, J.S. 1985. Deforestation issues in developing countries. The case for an accelerated investment program. Proceedings of the Twelfth Commonwealth Forestry Conference. pp 47-59.
General: Economics

Sprent, J.I. 1985. Nitrogen fixation in arid environments. In: Plants for Arid Lands. George Allen and Unwin, London.
General: Soils
Data on the nodulation ratio of N-fixing plants. Dry soils often high in N as nitrate. Deep rooted N-fixers (*Prosopis*) may contribute to high nitrate levels through mineralisation of litter. Legumes require moisture and will not fix N under stress.

Squire, R.O. 1983. Review of second rotation silviculture of *Pinus radiata* in southern Australia: Establishment and expectations. In: IUFRO Symposium on Forest Site and Continuous Productivity, Seattle, Washington, August 1982. General Technical Report, Pacific Northwest Forest and Range Experiment Station, US Dept. of Agriculture Forest Service (1983), No. PNW-163.
Australia: Soils
Improved performance of second rotation crops in recent years associated with increased availability of water (mulching) and increased nutrients (fertiliser application, use of legumes and leaving logging residues). Nitrogen can promote increased water efficiency by its effect on the stomata.

Statham, P. 1990. The Sandalwood industry in Australia: a history. In Proceedings of the Symposium on Sandalwood in the Pacific, April 1990, Honolulu, Hawaii. US Department of Agriculture, Forest Service, General Technical Report PSW-122. p 26-38.
Australia: exploitation
A history of exploitation in Australia.

Steinbeck, K. and Skinner, T.M. 1984. Growing short-rotation forests in the southeastern USA. In: Bioenergy 84. Proceedings of conference June 1984 Goteborg, Sweden. Vol II. Biomass Resources. Elsevier Applied Science Publishers.
USA: Soils
Mixtures of *Platanus occidentalis* and *Liquidambar styraciflua* with N-fixers *Alnus glutinosa* and *Robinia pseudoacacia*. After 5 years no consistent differential effects of tree species on soil nutrients, pH or organic matter. Lack of soil N accretion probably caused by rapid growth of *R.pseudoacacia* and poor survival of *A.glutinosa*.

Streets, R.J. 1962. Exotic forest trees in the British Commonwealth. Clarendon Press, Oxford.
General: Management

Styles, B.T. 1991. Personal communication.

Sweet, G.B. and Burdon, R.D. 1983. The radiata pine monoculture: an examination of the ideologies. New Zealand Journal of Forestry 28 (3): 325-326.
New Zealand: General

Tasmania Forestry Commission 1989. Forest Practices Code (draft). Forestry Commission, Tasmania. pp 89.
Australia: Management
A detailed code of practice for logging native forests.

Tham, A. 1988. Yield prediction after heavy thinning of birch in mixed stands of Norway spruce (*Picea abies* (L) Karst.) and birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.). Swedish University of Agricultural Sciences, Department of Yield Research, Report 23.
Sweden: Yield. Management
The highest total yield was found when spruce was mixed with a shelter-wood of 800 birch/ha. At higher densities spruce production was lower than in a pure spruce stand. A shelterwood of 500-600 birches/ha is recommended. The shelterwood should be retained for 20-30 years.

Thomas, J.W. 1979. Wildlife habitats in managed forests, the Blue Mountains of Oregon and Washington. Agric. Handbook No. 533. pp. 512. USDA: Forest Service.

Tisseverasinghe, A.E.K. and Satchithananthan, S. 1957. The management of Sundapola plantation. Ceylon Forester 3 (1): 82-93.
Sri Lanka: Management. Yield
A summary of data from a 50 year old mixed plantation of *Artocarpus integrifolius* and *Swietenia macrophylla*.

Tiwari, K.M. 1970. Interim results of intercropping miscellaneous species with main crop of taungya plantations to increase the productivity. Indian Forester 96 (9): 650-653.
India: Yield
Multipurpose species have been introduced in the interspaces of sal taungya lines. An additional yield of approx. 1 tonne/ha/yr was obtained on a four-year rotation. Species used include *Albizia procera, Bauhinia variegata, Cassia fistula* and *Ougenia oojensis*.

Tourney, J.W. 1947. Foundations of silviculture upon an ecological basis. John Wiley and Sons.
General: Textbook
A textbook with a detailed discussion about mixed stands.

Tu, M.Z. and Yao, W.H. 1984. Studies on the influences of soil pH by different plant communities. Tropical and Subtropical Forest Ecosystem, Ding Hu Shan Forest Ecosystem Station, China 2: 110-113.
China: Soils
A study of 26 plantations showed that a mixture of legumes and non-legumes increased pH. *Dalbergia odorifera* and *Cassia siamea* gave best results. Planting *Calamus tetradactylus* recommended to increase pH and profits.

Turner, J. 1983. Maintenance and improvement of forest productivity in Australia. In: IUFRO Symposium on Forest Site and Continuous Productivity, Seattle, Washington, August 1982. General Technical Report, Pacific Northwest Forest and Range Experiment Station, US Dept. of Agriculture Forest Service (1983), No. PNW-163.
Australia: Soils. Management

Describes silvicultural activities (site preparation, weeding, fertiliser application) to enhance productivity. Major gains in productivity are made in the establishment phase.

Turvey, N.D., Attiwill, P.M., Cameron, J.N. and Smethurst, P.J. 1984. Growth of planted pine trees in response to variation in the densities of naturally regenerated acacias. Forest Ecology and Management (7): 103-107.
Australia: Soils. Management
No growth benefits to the pine could be detected. It is speculated that acacia is not the most appropriate nitrogen fixer to be used.

Uhart, E. 1962. *Les reboisement et le développement de Madagascar.* (Reafforestation and development of Madagascar.) Bois et Forêts de Tropiques No. 83: 15-29.
Madagascar: Management
A policy of reforestation in Madagascar is discussed.

Un, C.R., Bing, J.Y. and Yung, N.Y. 1979. Study in mixed planting. Quarterly Journal of Chinese Forestry.
China: Management
Taiwania cryptomerioides and *Paulownia taiwania* in mixture.

Velez, R. 1991. *Uso del fuego en selvicultura.* Paper, Theme 5.2, 10th World Forestry Congress, Paris, 1991. Proceedings Vol.2: 461-470.
General: Fire

Villamar, C.A. 1979. Silvipasture establishment for range type production of water buffalo. Sylvatrop Phillipine Forest Research Journal 4 (1) pp 17-21.
Philippines: Management
Leucaena leucocephala (1,360/ha, 82% survival) and *Gmelina arborea* (202/ha, 52% survival) in *Stylosanthes guyanensis* and *Themeda triandra* grasslands.

Vink, A.T. 1970. Forestry in Suriname. Landbosbeheer, Suriname Forest Service.
Suriname: Management
Rather intensive systems of enrichment- and strip-planting are described.

Voogd, C.N.A. de 1928. *Over kunstmatige menging van djati met wildhout.* (On artificial mixing of teak.) Tectona 21: 527-533. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 612.
Indonesia: Management
Mixing advantages can be obtained by mixing with species growing just below the teak trees. Mixing species should stay green during the dry season, be easy to grow and produce a marketable product.

Voron, P. 1979. The effect of industrial air pollution on the health of forest plantations in the Carpathian foothills. Lesovodstvo i Agrolesomeiioratsiya 53: 53-57.
USSR: Environmental
In a study of pollution effects mixed stands were more resistant than pure.

Waage, J. 1990. Exploration of biological control agents of *Leucaena Psyllid* in tropical America. F/FRED Coordinating Unit, Bangkok. pp 144-152.
Central America: Pests
Describes the insect and its predators in the native range.

Watt, A. 1990. Insect pest population dynamics effects of tree species diversity. In Ecology of Mixed Species Stands of Trees. British Ecological Society and IUFRO Div 2.01 Symposium, Edinburgh.
UK: Environmental, pests and diseases

Way, M.J. 1977. Pest and disease status in mixed stands vs. monocultures; the relevance of ecosystem stability. In: The Origin of Pest, Parasite, Disease and Weed Problems. pp 127-138, Blackwell, Oxford.
Environmental: Pests and diseases
It is emphasized that diversity in itself is no guarantee against pests and diseases. Diversity may decrease attacks through provision camouflage, barriers, hazards or alternative hosts.

Wepf, W. 1955. *Het begrip menging in djaticulturen.* (Mixing in teak plantations.) Tectona 43: 290-294. Noted in Indonesian Forestry Abstracts, PUDOC, Wageningen, 1982. Abstract 596.
Indonesia: Management
The aim of mixing should be a luxuriant undergrowth. Use should be made of the natural plant community.

Whitehead, D. 1981. An ecological overview of plantation forestry. New Zealand Journal of Forestry 26 (1): 14-19.
New Zealand: Environmental, ecology
The ecological hazards of plantation forestry are discussed. Some of the criticism of plantation forestry found to be unjustified.

Whitehead, D. 1982. Ecological aspects of natural and plantation forests. Forestry Abstracts 143 (10): 615-624.
New Zealand: Environmental, ecology
High diversity does not always result in high stability and productivity. There are examples of pure stands with stable structures.

Whitmore, J.L. 1973. Myths regarding Hypsipyla and its host plants. In: First Symposium on Integrated Control of Hypsipyla. IICA-CTEI-Turrialba, Costa Rica.
Environmental, Pests and diseases
Quantification studies are needed to learn whether, and if so how much, less shaded seedlings are attacked by Hypsipyla.

Whitmore, J.L. 1991. Personal communication.

Whitmore, T.C. 1984. Tropical Rain Forests of the Far East (2nd ed.). Oxford University Press (UK) pp 352.
Far East: Ecology
A text book of rain forest ecology.

Wilcox, B.A. 1982. *In situ* conservation of genetic resources: determinants of minimum area requirements. In: World National Parks Congress, Bali 18 - 30. New Directions.

Wilde, S.A. 1964. Changes in soil productivity induced by pine plantations. Soil Science 97: 276-278
USA: Soils
Analysis of 156 *Pinus banksiana, P. resinosa, P. strobus* stands, 10-50 years old. By far the best indicator of fertility status of reforested soil is the content of organic matter, strongly correlated with CEC and total N supply. After age 35-40 years, pine stands usually correct temporary soil deficiencies caused by logging, burning etc.

Will, G.M. 1964. Dry matter production and nutrient uptake by *Pinus radiata* in New Zealand. Commonwealth Forestry Review 43: 57-70
New Zealand: Soils. Yield
Rooting to 6 m in pumice soils. High growth rate attributable to high rainfall (1500 mm) and high solar energy. Annual increment of dry matter 20 tons/ha (Site Quality II) to 45 tons (Site Quality I). Maximum growth the first 10 years. Thereafter no fertilization is necessary, decomposing litter and slash meet most of trees' demands.

Will, G.M. and Ballard, R. 1976. Radiata pine soil degrader or improver? New Zealand Journal of Forestry 21 (2): 248-252.
New Zealand: Soils

Where soil deterioration has been observed under pure coniferous forests, it has been caused by mismanagement and exploitation. This can be rectified by fertilizers.

Williamson, M. 1990. War and forests: South Vietnam. New Zealand Forestry: 18-21.
Viet Nam: Management
Dipterocarps (*Dipterocarpus alatus* and *Hopea odorata*) under a nurse crop of *Acacia auriculiformis*.

Wilson, E.O. (Ed). 1988. Biodiversity. National Academic Press, Washington, D.C. 521 pp.

Wilson, W.L. and Johns, A.D. 1982. Diversity and abundance of selected animal species in undisturbed forest, selectively logged forest and plantations in East Kalimantan, Indonesia. Biological Conservation 24: 205-218.
Indonesia: Wildlife
Small plantations (6 to 24 months old) of *Pinus, Eucalyptus, Gmelina, Anthocephalus* and *Paraserianthes*. Wildlife using plantations come in from surrounding forest, few can survive in a monoculture.

Wilten, W. 1955. *Aspects de la sylviculture au Mayumbe*. Bull. Agric. Congo-Belge Vol 46 (2): 319-328.
Zaire: Management, regeneration
Methods of raising *Teminalia superba* are explained.

Wimbush, S.H. 1945. The management of cypress plantations in Kenya. Forest Department of Kenya, Pamphlet No. 11.
Kenya: Management. Environmental, pests and diseases
Because of the perceived hazards of pure cypress plantations, mixing cypress with broadleaves is recommended. *Grevillea robusta* is one of the species recommended. A regime is proposed.

Woinarsky, J.C.Z. 1979. Birds of a eucalyptus plantation and adjacent natural forest. Australian Forester Vol. 42 (4): 243-247.
Australia: Wildlife
Diversity was compared between a plantation of *Eucalyptus botryoides* and an adjacent natural forest of mixed *Eucalyptus dives* species. Diversity was slightly higher in the natural forest.

Wood, P.J. and Dawkins, H.C. 1971. Forest monocultures in the tropics - ecological anxieties. Mimeographed Report, Oxford Forestry Institute Library. pp 3.
Tropics: Management
Plantation establishment is uncommon in polyspecific forests. Erosion can be serious on sandy soils. Deep rooted plantations transpire more water than grassland, but the effect of grazing, trampling or burning is more serious than the type of cover. Exclusion of large wild life causes overconcentration elsewhere.

Wuelisch, G. von, Muhs, H.J. and Gebarek, T. 1990. Competitive behaviour of clones of *Picea abies* in monoclonal mosaics vs. intimate clonal mixtures. Scandinavian Journal of Forest Research, 5(3): 397-402.
Germany: Yield
Competitive effect of clones of different provenances growing monoclonally or in mixture was examined. Competitive differences were detected. Positive competitive reactions can raise yields, and reduce risks through genetic diversity.

Young, A. 1976. Tropical Soils and Soil Survey. Cambridge University Press (UK).
The tropics: Soils
A text book on tropical soils.

Zhai, M.P., Xia, Z.Y. and Cao, Y.Y. 1987. Element contents and their annual and seasonal variations in the leaves of trees in *Pinus tabulaeformis* plantations. Scientia Silvae Sinicae 23(3): 286-298.
China: Soils
Levels of N, P, K, Ca and Mg were 5% to 317% higher in *Acer truncatum* leaves than in the pine. It is concluded that the maple is a suitable species for growing in mixture with the pine.

Zhang Xian, Xu Guang, Zhen Hong, Zhon Xu and Zhon Chong. 1980. Repeated planting of *Cunninghamia lanceolata* and soil toxicity. In Ecological studies on the artificial *C.lanceolata* forests. Institute of Forestry and Pedology. Academia Sineca.
China: Soils
Repeated planting of *C.lanceolata* results in "soil sickness" attributed to "more intense activity on the oxidation of certain polyphenol compounds containing methoxyl".

Zwaan, J.C. de. 1981. The silviculture of blackwood (*Acacia melanoxylon*). South African Forestry Journal 121: 38-43.
South Africa: Management
A review of the performance and requirements of blackwood. Mixture with *Pinus radiata* being tried because that species was thought to be deeper rooting and more wind stable, but proved just as liable to wind throw. Blackwood/Eucalyptus (*E.diversicolor* and *E. microcorys*) mixtures also unsuccessful, blackwood suppressed.

Zwolinski, J.B. 1990. Intensive silviculture and yield stability in tree plantations: an ecological perspective. South African Forestry Journal 155: 33-36.
General: Environmental, ecology
Puts silviculture of plantations in an ecological setting and recommends some ecologically sound practices.

APPENDIX 2

SOILS

One of the major concerns expressed on the risk of creating monospecific plantations is that they cause a loss of fertility and soil degradation. It is therefore worth considering in some detail the salient features of soils on which afforestation in the tropics and sub-tropics mostly takes place and the interaction between tree crops and the soil.

Some characteristics of tropical soils.

The sites used for forest plantations in the tropics are, as elsewhere, often only available because they are unsuited to agriculture or have been made available for plantations after being degraded by poor agricultural practices. The soils tend to have certain common characteristics.

Ferralsols and Acrisols are the biggest soil groups in the tropics accounting between them for 37% of tropical soils. They are old soils, often deep, but intensely weathered and therefore lacking in primary minerals which provide the reserves of nutrients needed for plant life. They are leached of nutrients particularly on sites subject to high rainfall and are acidic which adversely affects the capacity of the topsoil to hold nutrients in a form available for plant use. Nevertheless under undisturbed forest vegetation these soils are capable of carrying a large volume of vegetation on the higher rainfall sites because the nutrient supply available in solution in the topsoil is maintained by the rapid decomposition and mineralization of the litter layer on the soil surface. Even in the drier phases of these soils (*miombo* in Africa, *cerrado* in South America) where fires are frequent adequate fertility can be maintained if the organic matter content of the soils is not grossly depleted.

Disturbance of these sites, whether for agriculture or by clearing for forest plantations, involves the risk of damaging the soil structure, particularly if heavy machinery is used. Exposure of the soil and removal of organic matter by, for example burning, both damages the soil structure and promotes the loss of nutrients through leaching.

Arenosols and Regosols form a small proportion of tropical soils. They are coarse textured sandy soils having a low nutrient content and low water retaining capability; as such they are of marginal use to agriculture and are therefore often available for forest plantations.

Lithosols and the lithic (stony and shallow) phase of other soils are common in the tropics. These soils are frequently subject to agricultural mismanagement on steep hillsides. Though seldom suitable for large scale commercial forest plantations, forestry may be the most appropriate land use to rehabilitate them. Accumulation of organic matter promotes soil formation.

Nitosols, clayey red tropical soils, are more fertile than the ferralsols and acrisols and are mostly under agricultural crops, but in the highlands of East Africa many of the conifer plantations have been established on nitosols unsuited to agriculture by reason of steep slopes or high altitudes and low temperatures. These soils are less prone to nutrient deficiencies, but are liable to erosion if mismanaged.

Vertisols are heavy, often black, cracking clays which develop where there is a long dry season, e.g. in the Deccan (India), Gezira (Sudan), Kanoplains (Kenya). Though tending to be rather low in nitrogen and low in exchangeable potassium and available phosphorus, they have a high cation exchange capacity and can be used successfully for agriculture. Because of their high clay content, however, they are difficult to work and may be available for establishing forestry plantations. Organic matter content tends to be low.

Cambisols and Luvisols are relatively young, fertile soils that will mostly be reserved for agriculture.

Soil Nutrients

The sixteen chemical elements known to be essential for plant growth are commonly considered in four categories (Young 1976)

Elements — Oxygen, Hydrogen and Carbon supplied from air and water and not normally considered as nutrients.

			Available form
Primary nutrients	Nitrogen	N	NH_4^+ & NO_3^-
	Phosphorus	P	H_2PO_4
	Potassium	K	K^+
Secondary nutrients	Calcium	Ca	Ca^{2+}
	Magnesium	Mg	Mg^{2+}
	Sulphur	S	SO_4^{2-}
Trace elements	Iron	Fe	Fe^{2+} Fe^{3+}
	Boron	B	Various anions
	Zinc	Zn	Zn^{2+}
	Copper	Cu	Cu^{2+}
	Manganese	Mn	Mn^{2+}
	Molybdenum	Mo	MoO_4^{2-}
	Chlorine	Cl	Cl^-

Source: Young (1976)

Nitrogen is the nutrient most frequently deficient in the tropics. Most soil nitrogen is derived from the mineralization of organic matter. In the organic form it is not available to plants and must be converted by fungi and bacteria to the mineral form in a 3-stage process; decomposition to ammonia (NH_3), conversion of the ammonium cation (NH_4^+) by nitrifying bacteria first to nitrite (NO_2^-) then to nitrate (NO_3^-) in which form it is mostly taken up by plants. In this form it is highly soluble and susceptible to leaching and therefore a continuing supply is essential; the benefits of large doses of artificial N fertilizer are mostly lost by leaching.

Nitrogen is introduced into the nutrient cycle by the working of nitrogen fixing bacteria which are either free living *Azotobacter* (rare in the tropics) or symbiotic *Rhizobium* on the roots of some legumes and non-symbiotic bacteria on a range of genera. Fixed ammonia in the subsoil can make some contribution to the nitrogen economy and it has been estimated rainfall can contribute up to 5 kg/ha/year (Ewell 1986)

Phosphorus is required by plants and is present in the soil in much smaller quantities than nitrogen. Most of the P in the soil is held in a form unavailable to plants but is converted to the available form (the phosphate anion) at a slow rate. The rate at which P changes from the unavailable to the available form is much slower than the rate at which healthy plantations need to take up the nutrient, therefore the recycling of P in the organic matter is an essential contribution to the supply of this nutrient. A problem in many soils, especially acid soils, is the tendency for P to become fixed to clay particles. The rate of release is extremely slow and, though this is an advantage in that the P is available over a long period, it is unavailable at times of rapid uptake by a growing crop. But organic P is less readily fixed than inorganic P and for this reason, among others, it is important to maintain the organic content of the soil.

Potassium is present in the soil in larger quantities than P and is less frequently deficient. It is taken up by plants as the cation, is easily leached and can be deficient in rainforest and sandy savanna soils.

Calcium and Magnesium are taken up as cations and therefore can be deficient on strongly leached soils.

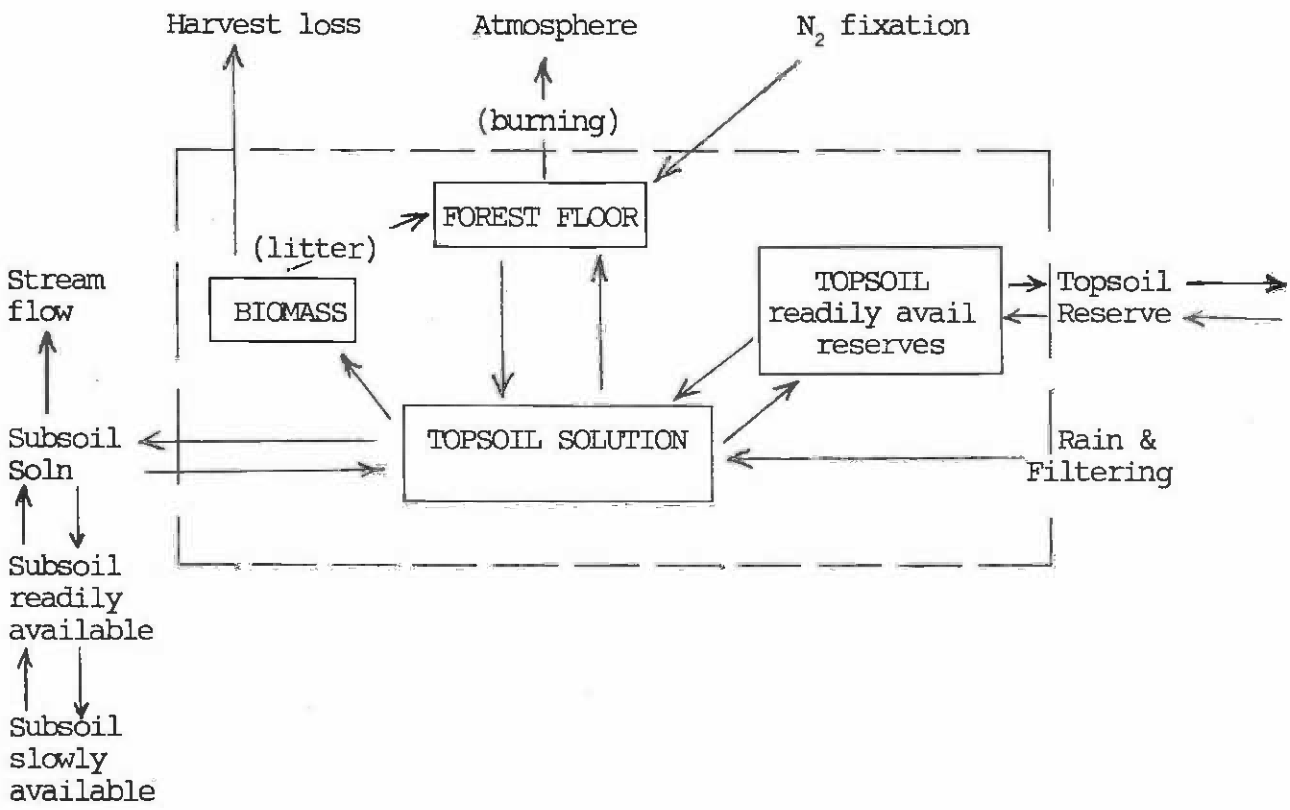
Sulphur is taken up as the anion and can be lost by leaching and by volatilization during burning. It may be deficient in soils low in organic matter.

Organic matter has a profound effect on the availability and presence of nutrients in the topsoil solution. It also affects the structure and moisture retaining capacity of soils. There is a complex interaction involving not only these nutrients (P deficiency inhibits N uptake etc; Ca excess can cause chlorosis by inhibiting the uptake of Fe) but also between the organic content of soils, water availability and nutrients.

A Soil Nutrient Flow Model.

In discussing the interaction of crops and soils it is helpful to have a model of nutrient flows. Figure 1, constructed for conditions in the pine plantations at Usutu, Swaziland can be used as a general model.

Figure 1 Nutrient Flow Model, Usutu, Swaziland.



Source: Morris (1986)

The forester is primarily interested in the biomass component (and usually specifically in the tree stem fraction of the biomass), but for a given regime of temperature, rainfall and competition, the growth of the biomass is dependent on the nutrient supply from the topsoil. At any one time the quantity of nutrients held in solution is not large in comparison with the total soil nutrient reserves and the quantity of P, in particular, may be small in comparison to the amount held in the living and dead biomass.

Table 1 Nutrients in the topsoil

		available N&P and exchangeable K, Ca & Mg				
		N	P	K	Ca	Mg
			(Kg/ha)			
			Usutu, Swaziland - pine			
In top 1 m	1st rotation	3170	5	828	288	456
	2nd rotation	2789	7	842	279	342
Biomass 17 years		551	73	383	238	88
Litter	2nd rotation	2122	113	130	308	146

Source: Morris (1986)

		Nigeria - *Gmelina arborea*			
In top 1 m	1215	2	12	347	57
Biomass 14.5 yrs	157	12	337	66	93
Litter	6	1	3	5	5

Source: Chijioke (1980)

		Nigeria - *Gmelina arborea*			
Soil Reserves	1725	54	-	3491	1508
Biomass 10 yrs	960	371	-	2425	614
Litter	30	1	-	48	11

Source: Nwoboshi (1983)

In comparison to the nutrients held in the combined biomass and litter the quantities of N and Ca available in the soil would appear to be adequate; the proportion of K and Mg depends on the site and species but the quantity of available P is very small. These quantities and proportions will vary between sites and between species, but it is to be inferred that the supply of some nutrients in solution, notably P, can easily become limiting especially at times of maximum growth in the development phase of plantations. The maintenance of available soil nutrients in the topsoil is critical to healthy growth of plantations.

Inputs of nutrients arise from

- Rainfall and the filtering effect of foliage. In Usutu this effect was considered to be small, but a generalized figure for the tropics of 5-18 kg/ha/yr N and <1 kg/ha/yr P has been calculated (Ewel 1986).

- Weathering of primary minerals and movement from subsoil to topsoil. The quantities involved are hard to estimate and must vary with the availability of primary minerals in the subsoil, but the rate of replacement will always be slow. It is doubtful whether this source of nutrients is adequate to replace the losses involved in short rotation forest plantations on highly weathered soils.

- Nitrogen fixation. This is covered in more detail in a later section of this Appendix. On some tropical sites as much as 58 kg/ha/yr N has been recorded as being fixed. This process can make a major contribution to nitrogen availability.

Losses from the system occur through

- Removal of logs at harvesting. This can be quite high, but can be reduced by leaving branches, twigs, bark and leaves in the plantation.

Table 2 Nutrients lost at harvesting

	Yrs.		N	P	K	Ca	Mg
					(Kg/ha)		
Usutu pine	17	(1)	257	43	159	123	37
Nigeria Gmelina	6	(2)	182	38	136	108	51
Gmelina	14	(2)	138	11	169	155	52
Brazil pine	6	(2)	99	21	31	25	17
Nigeria Gmelina	10	(3)	754	282	-	2174	528

Sources: (1) Morris (1986); (2) Chijioke (1980); (3) Nwoboshi (1983)

These figures show that quantities can vary with species and locality, but it can be appreciated that significant quantities of nutrients are involved.

Over a long rotation it is possible that much of the nutrients lost in harvesting can be replaced by nitrogen fixation and by weathering of parent soil, but a succession of short rotations will drain the nutrients. Phosphorus is accumulated in higher concentrations in the stems of young pines, therefore short rotations are particularly likely to drain the P supply.

- Burning slash. This can occur at the time of initial clearing and at each harvest. The quantities involved have been calculated at Usutu. The burning of slash provides an initial boost of some nutrients (P, K, Ca, Mg) in the form of ash, but N and S are volatilized and lost. Most of the nutrients released from the ash are lost through leaching before they can be utilized by young plants.

Table 3 Nutrients lost in burning - Usutu

	N	P	K	Ca	Mg
			Kg/ha		
Pinus patula 17 yrs	266	19	11	16	15

Source: Morris (1986)

- Leaching. Losses due to leaching under forest cover were considered to be small in Usutu (Morris 1986), but they can be significant on sandy soils, and in high rainfall particularly during the clearing phase. The maintenance of vegetative cover including that arising from the re-invasion of cleared sites by indigenous vegetation is helpful in controlling leaching.

- Run off can involve the loss not only of large volumes of soil, but also of the available nutrients in the topsoil. In Trinidad this can amount to 153 tonnes/ha in a year which is equivalent to 1 cm of topsoil (Bell 1973). In Usutu, however, loss of nutrients by erosion and run off was not considered to be serious.(Morris 1986)

Nutrient sinks. The nutrient cycle

-> Soil solution -> Biomass -> Litter -> Soil solution

is of great importance. Given the generally slow rate of replacement of nutrients into the ecosystem, the potential for large losses from logging and clearing using fire and the varying rate of demand, depending on the season and the stage of development of the plantation, the buffering function of organic matter in the topsoil is highly significant. If the nutrients are held in the litter and become unavailable to the topsoil solution, then nutrient deficiencies will occur. In Usutu it was estimated that the weight of nutrients in the forest floor litter in a 17 year old plantation at 1150 m altitude was N - 557, P - 30, K - 34, Ca - 81, Mg - 38 kg/ha, but that at 1450 m these values were approximately doubled. The rate of litter production was similar at both altitudes and was roughly equivalent to the rate of litter build up at the higher altitude, indicating that there decomposition was very slow.

The role of biological factors.

Microfauna activity.

Earthworms in temperate zones are probably the most intensively researched of the soil fauna. Earthworms play an important role in fragmenting leaf litter and incorporating it into the topsoil; the number and weight of earthworms in a stand of spruce in England has been increased by the admixture of alder into the stand, and to an even greater extent by adding pine; the mineralization of N and P was also increased (Brown and Harrison 1983). Earthworms are less common in the tropics and their role has been taken over to a large extent by termites, which not only fragment the litter but also mineralize the nutrients in the litter. Whereas earthworms cause a vertical mixing of soils, termites create a lateral concentration of nutrients into termitaria and may as a result deplete the forest floor of organic matter (Young 1976; Trapnell in Chaffey 1978). Other microfauna - millipedes, mites, beetles - generally fragment the litter which renders it into a form better suited to decomposition by microflora. The activity of microfauna is strongly influenced by leaf nutrients and chemicals such as phenols. The inclusion into a pure stand of species with leaves favoured by microfauna will promote their activity, leading to faster litter breakdown and the more rapid incorporation of organic matter into the soil and thus the faster recycling of nutrients. In Costa Rica in a plot which simulated a species rich successional mixture, 50% by weight of *Cordia alliodora* leaf litter (and 50% of elements other than nitrogen and sulphur) had decomposed within six weeks; in a pure plantation after fifteen weeks only 22% by weight and less than 50% of nutrients (except phosphorus and potassium) had decomposed (Babbar and Ewel 1989).

Microflora.

Bacteria are most beneficial in decomposing organic matter and are essential in the nitrogen cycle; fungi also have an effect. Antagonisms occur between microflora and a change in the forest floor condition may shift the microbiological equilibrium to favour organisms antagonistic to N fixing bacteria (Florence 1967). The conversion of short leaf pine/hardwood stands in south east USA to pure pine stands has lowered the pH which in turn may have inhibited the activity of bacteria and actinomycetes antagonistic to *Phytophthora cinamoni*, which now is a problem in these stands. *Fomes annosus* also occurs and it is possible that it is favoured by the lower pH of pine litter (Florence 1967). The symbiotic role of mycorrhizae in promoting the uptake of nutrients is well known; *Suillus variagatus* which occurs on *Pinus silvestris* but not on spruce can degrade protein very effectively leaving up to 87% in solution in the soil where it can be taken up by the spruce; this may account for the enhanced growth of spruce when pine is introduced into the stand (Ryan and Alexander 1990). In Usutu the form and number of the mycorrhizae on *P.patula* changed in second rotation crops which were in check;

this change in the mycorrhizae and the growth check was attributed to the accumulation of litter, which may have caused both a reduction of available nutrients and an increase of toxins (Robinson 1973).

Nitrogen-fixation.

The effect of nitrogen-fixation has been well documented in North America (Binkley 1983,1984,1990; Binkley and Greene 1983; Hansen and Dawson 1982; Friederich and Dawson 1984; Schlesinger and Williams 1984). The species involved have generally been alder (*Alnus rubra, A.sinuata* and *A.glutinosa*)and autumn olive (*Elaeagnus umbellata*) acting on Douglas fir (*Pseudotsuga menziesii*), walnut (*Juglans nigra*) and poplars. Beneficial effects have occurred when nitrogen has been in short supply, but where there has been an adequate supply of other nutrients to keep the nitrogen fixing species growing healthily. Legumes require moisture and when under stress will not fix nitrogen (Sprent 1985), though it has been suggested that alder and *Robinia pseudoacacia* may release nitrogen in response to competition-induced stress (Dawson et al. 1983; Friederich and Dawson 1984). A close association is needed of the nitrogen-fixer with the benefiting species and growth has been shown to be correlated with quantities of N fixed in the topsoil (Paschke et al. 1989). But it has been suggested (Ewel 1986) that nitrogen-fixing species mostly use up the nitrogen they manufacture and only release it through their litter, and it has certainly been observed that leaf litter from *A.glutinosa* and *E.umbellata* used as a mulch enhanced the growth of poplars on prairie soils (Carlson and Dawson 1984). The evidence on this point is confusing. There is also evidence that *Picea sitchensis* did not respond to increased nitrogen (585 kg/ha) made available by *A.glutinosa* (Malcolm et al. 1985).

On nitrogen-rich soils the presence of nitrogen-fixing plants can be deleterious, because they compete for light, moisture and other nutrients. In Australia the introduction of acacias into stands of *P.radiata* and *P.elliottii* on sandy podzols resulted in a depression in growth as a result of increased competition, even though the soils were low in N (Turvey et al. 1984). On the other hand *Daviesia mimosoides* growing under natural *Eucalyptus dives* and *E.divesicolor* on red kraznozem soils on exposed ridges was considered to have had a beneficial effect on growth despite the fact that the *D.mimosoides* had only 50% nodulation and was fixing only 4 to 7 kg of N per ha per year (McColl and Edmonds 1983).

In Hawaii there is a well documented example of the benefit of introducing nitrogen-fixing species (*Albizia falcataria* and *Acacia melanoxylon*) into *Eucalyptus saligna* plantations on an abandoned sugar estate (DeBell et al. 1985, 1987, 1989). On a site receiving 5000 mm rain nitrogen was increased in the topsoil and there was a significant and marked growth in the eucalyptus, but on a dry site there was no benefit and on one site the *Albizia* died. In the Niligiris in India there is a less reliable account of *Acacia menziesii* having a beneficial effect when grown under *Eucalyptus globulus* (Samraj et al. 1977). The introduction of leguminous trees, *Erythrina, Gliricidia, Acacia auriculiformis, A.crassiocarpa* and *A.polystachya* into eucalyptus plantations near Chittagong, Bangladesh has been proposed (Davidson 1986), but there is no record of any effects.

Nitrogen fixation is often associated with legumes, although nodulation is only sporadic in the Caesalpinioideaea (Sprent 1985), but in fact non-symbiotic fixation of nitrogen (alder type nodules) has been recorded as occurring on nearly 200 species in 20 genera other than legumes; this included 24 species of *Casuarina* which are probably the most significant species for the tropics (Bond 1983). The quantities of nitrogen fixed vary considerably.

Table 4 Amount of Nitrogen Fixed by Some Species

	kg/ha/yr	
Casuarina equisetifolia in N.Africa	58	(Kormanik 1979)
Elaeagnus umbellata	178	(Paschke et al. 1989)
Acacia holosericea	6.4	(McColl et al. 1983)
A.pulchella var *glaberrima*	2.2	
A.mearnsii	.8	
A.verniciflua	32	(Turvey et al, 1984)

Allelopathy

The inhibition of the growth of one species by exudates from another species is comparatively rare, but juglone from walnuts has noted as having this effect (von Althen 1968). In Indonesia there is an account of several species including *Leucaena leucocephala* and *Swietenia macrophylla* failing to thrive under *Melaleuca leucadendron* and allelopathy was considered a possible cause. In Australia the inhibition of the germination of seedlings of *Grevillea robusta* under old trees of the same species has been noted (Florence and Lamb 1974)

Nutrient deficiencies

Depending on the soil type, climate, method of establishing the tree crop and the nature of the crop any of the nutrients could become deficient. It is likely that N, P, K and possibly Ca are most likely to be limiting in the tropics (Lundgren 1980). The nutrients available in solution in the soil may be small in relation to the requirements of the biomass at any one time. N and P, in particular, are only slowly available from soil reserves, therefore the recycling of litter is an important source of these two nutrients. The requirements of the biomass and the drain on the nutrients in solution vary with the stage of development of the crop.

Taking Usutu pine plantations as an example:

- At the start of each rotation the exposure of the litter following harvesting results in rapid decomposition of organic matter and a flush of nutrients, but the rooting volume of the seedlings is small and they may suffer from lack of nutrients, particularly P and K; at the same time available nutrients are being leached away.
- Up to the age of seven years, nutrient requirements to maintain biomass production increase rapidly and K may remain in short supply.
- From seven to twelve years of age, biomass production requirements are still high but litter starts to build up and, if decomposition is slow, nutrient cycling may be inefficient thus putting P under pressure.
- From twelve years of age onwards biomass requirements remain fairly constant but litter build up continues; N and P may become deficient and at higher altitudes possibly Ca also.

A mixture of species may be useful (but not necessarily at Usutu):

- at time of establishment another species used as an in-filler can make use of excess nutrients and help recycle them; this effect can be achieved by allowing weed growth or through the use of ground cover.
- in helping to decompose the needle mat under the pines from seven years onwards; a more open stand and the encouragement of a natural understorey might achieve this.

A comparison has been made between indigenous forests and *Gmelina* plantations in Nigeria and between indigenous forests and both pine and *Gmelina* plantations in South America (Chijioke 1980). He was unable to demonstrate that monospecific plantations lead to a more rapid depletion of soil nutrient reserves than would mixtures having the same biomass production, the same rotation length and the same proportion of the crop removed in harvest. Despite the large quantities of N immobilized by *Gmelina* and pines it was present in more than optimum levels in the soil and harvesting represented no threat to the future N status. K which was immobilized in greater quantities, and possibly P, may become limiting.

In Kenya measurements were made to compare soils under second and third rotation conifer crops and under indigenous forest (Robinson 1967; Robinson et al. 1966). The results were not conclusive, but only a slight decrease in nutrient availability could be detected in cypress and pine plantations and there were indications that the drop in nutrient availability occurred during the establishment phase of each rotation as a result of cultivation under the *taungya* system, while fertility increased in the period the trees were on the ground. On one site bulk density decreased and pH increased under the plantations, indicating a general improvement in soil conditions.

APPENDIX 3

SPECIES MIXTURES

This is a collection of most of the mixtures that were found in the literature. Where possible some indication has been given on the success of the mixture. Most of the mixtures listed are in fact experimental. The following mixtures are thought to have been used as general forestry practice.

Queensland
Araucaria cunninghamii Pines
but practice discontinued
Vietnam
Eucalyptus tereticornis over *Acacia auriculiformis*
more than 10,000 ha thought to have been established, but no information available to date on success.
Kenya
Cypress *Grevillea robusta*
Practice discontinued by mid 1950s
Togo
Eucalyptus torelliana *E.tereticornis*
considered a success.
Sri Lanka
Swietenia macrophylla *Tectona grandis*
Artocarpus integrifolius
highly successful at Sundapola

The use of nurse species to shade mahoganies is standard practice in many tropical countries. In West Africa the practice has been abandoned in francophone countries, but is still continued in Nigeria.
Indonesia
Teak *Leucaena leucocephala* used as a nurse to establish the teak
Now seriously affected by *Heteropsylla cubana*

MAIN SPECIES	SECONDARY **(Nurse)**	**SOURCE**
AUSTRALIA - Queensland		
Araucaria cunninghamii	*Pinus elliottii*	**Nielsen 1991**
planting hoop pine under slash pine resulted in better growth (increased nitrogen uptake).		
	P.taeda, P.patula	
A.bidwillii	*P.elliottii*	**Nielsen 1991**
- Victoria		
Flindersia brayleyana	Araucaria cunninghamii	
F.brayleyana able to recover and make a crop when released.		
E.sieberi with	*Acacia longifolia*	**Smith et al 1989** also
E.botryoides & *E.sideroxylon*		
beneficial effect on height growth of Eucalyptus		
Pinus radiata or *Pinus elliottii*	*Acacia spp.*	**Turvey et al 1984**

The effects of naturally regenerated acacias were investigated. No positive effects were detected.

BANGLADESH

Calamus spp	*Shorea robusta* *Pinus oocarpa*	Davidson 1986

BRAZIL

Eucalyptus urophylla	*Leucaena leucocephala*	Moraes de Jesus 1989
Piptadenia macrocarpa *Astronium urundeuva* *Moqinia polymorpha* *Colubrina rufa* *Tabebuia impetiginosa*		Garrido & Poggiani 1979
Pinus caribaea v. hondurensis	*Liquidambar styraciflua*	Novais & Poggiani 8

Leaf heterogeneity appears to increase litter decomposition and nutrient cycling.

BURKINA FASO

Dalbergia sissoo	*Eucalyptus tereticornis*	CTFT 1991

Experiment established in 1967. Treatments have favoured D. sissoo.

Eucalyptus camaldulensis	*Gmelina arborea*	CTFT 1991

Experiment established in 1980.

BURUNDI

Eucalyptus grandis	*Acacia elata*	CTFT 1991

Experiment established in 1987. Poor survival for *A. elata*.

CAMEROON

Khaya senegalensis	*Dalbergia sissoo*	CTFT 1991

Experiment established in 1986.

Azadirachta indica *Khaya senegalensis*	*Dalbergia sissoo*	CTFT 1991

Experiment established in 1983.

Khaya senegalensis	*Eucalyptus camaldulensis*	CTFT 1991

Experiment established in 1983. Low survival for *Khaya*.

Pinus elliottii	*Entandrophragma cylindricum*	CTFT 1991

Experiment established in 1975. 90% *Pinus*.

Entandrophragma cylindricum "	*Pinus elliottii* *Mansonia altissima*	CTFT 1991

Experiment established in 1975. In 1977 P. elliottii was replaced by M. altissima. Growth was slow and survival high for E. cylindricum.

CHINA

Eucalyptus exserta with *Acacia auriculiformis* Barnes **1991**

CONGO

Acacia auriculiformis *Eucalyptus tereticornis* **CTFT 1991**
Experiment established in 1984.

Araucaria hunsteinii *Pinus caribaea* **CTFT 1991**
Experiment established in 1980. Constant height differences recorded.

Entandrophragma angolense *Letestua durissima* **CTFT 1991**
Acacia auriculiformis
Experiment established in 1982. Good condition but poor growth for *A. auriculiformis.*

Tectona grandis *Terminalia superba* **CTFT 1991**
Experiment established in 1988. Individual mixture.

COTE D'IVOIRE

Aucoumea klaineana *Tarrietia utilis* **CTFT 1991**
Khaya ivorensis "
Tieghemella heckelii "
Experiment established in 1964. *T. utilis* is the nurse crop. *T. utilis* grows well. Fast growth for *T. heckelii* on sands has been noted.

Gmelina arborea *Acacia auriculiformis* **CTFT 1991**
Experiment established in 1985. Insect attacks have been severe.

Triplochiton scleroxylon *Gmelina arborea* **CTFT 1991**
" *Khaya ivorensis*
" *Chlorophora spp.*
" *Mansonia altissima*
The experiments with *Gmelina arborea* were established in 1961, the others in 1928.

Terminalia ivorensis *Cedrela odorata* **CTFT 1991**
Experiment established in 1977. *C. odorata* suppresses *T. ivorensis.*

Khaya grandifoliola *Cedrela odorata* **CTFT 1991**
Khaya ivorensis "
Khaya senegalensis "
Experiments established in 1977. *Cedrela* is the nurse and grows fastest. *K. senegalensis* did poorly.

Aucoumea klaineana *Tarrietia utilis* **CTFT 1991**
Khaya ivorensis "
Experiment established in 1965. *K.ivorensis* is promising; *A.klaineana* not.

Triplochiton scleroxylon *Tectona grandis* **CTFT 1991**
Experiment established in 1961.

Terminalia ivorensis *Terminalia superba* **CTFT 1991**
Experiment established in 1981. The mixture is promising.

Terminalia ivorensis *Cedrela odorata* **CTFT 1991**
Experiment established in 1965. Individual mixture with low density under a poison girdled forest. The low density has adverse effects on the stem form of *Cedrela*.

Khaya senegalensis *Terminalia ivorensis* **CTFT 1991**
Experiment established in 1965. 64 tree/hectare were planted.

Terminalia ivorensis *Entandrophragma utile* **CTFT 1991**
Experiment established in 1965. 41 trees/hectare planted in a poison girdled forest.

Terminalia ivorensis *Terminalia superba* **CTFT 1991**
Experiment established in 1977. Line mixture. Selectively thinned in 1980 and 1982. 252 *T. ivorensis* and 160 *T. superba* planted per hectare.

Cedrela odorata *Terminalia ivorensis* **CTFT 1991**
Experiment established in 1965. Individual mixture

Triplochiton scleroxylon *Khaya ivorensis* **CTFT 1991**
Experiment established in 1964. Individual mixture.

Tieghemella spp. *Triplochiton scleroxylon* **CTFT 1991**
" *Khaya ivorensis*
Experiment established in 1964. Individual mixture with *Khaya* or *Tieghemella*.

Cedrela odorata *Gmelina arborea* **CTFT 1991**
Experiment established in 1976. Line mixture. After four years *C. odorata* was co-dominant.

Khaya ivorensis *Tarrietia utilis* **CTFT 1991**
Experiment established in 1963. A promising mixture.

Triplochiton scleroxylon *Terminalia superba* **CTFT 1991**
Experiment established in 1963.

Khaya ivorensis *Tarrietia utilis* **CTFT 1991**
Khaya anthotheca "
Experiment established in 1981.

Acacia auriculiformis *Acacia mangium* **CTFT 1991**
Experiment established in 1985.

Acacia auriculiformis *Cocos nucifera* **CTFT 1991**
Acacia mangium
Casuarina equisetifolia
Experiment established in 1985. Two lines of each species separated by two lines of *C. nucifera*. Best growth has been recorded for *A. auriculiformis*.

FIJI

Cedrela odorata *Leucaena leucocephala* **Streets 1962**

Tectona grandis *Swietenia macrophylla* **Streets 1962**

FRENCH GUYANA

Carapa procera or *Swietenia macrophylla* or *Swietenia mahogani*	*Gmelina arborea* *Neopometia spp.*	**CTFT 1991**

Experiment established in 1978. 10% *Carapa* or *Swietenia* mixed with species not attacked by *Hypsipyla*. Poor growth for *Swietenia*.

HAWAII

Eucalyptus grandis)	(*Albizia falcataria*	DeBell **et al 1985**
Eucalyptus saligna)	(*Acacia melanoxylon*	

A.melanoxylon not so successful as *A.falcataria*

INDIA

Tectona grandis	*Dalbergia larifolia*	**Indian Forest Service 1934**
"	*Tephrosia candida*	
"	*Cajanus*	
"	*Leucaena glauca*	
"	*Swietenia macrophylla*	
"	*Cedrela toona*	
"	*"Bamboo species"*	
"	*Pterocarpus marsupium*	
"	*Artocarpus hirsuta*	

Tephrosia is an underwood species that seems efficient if introduced in the third year. Underplanting of *S. macrophylla* in 37 year old plantations had not yielded promising results, and the same experience was obtained with *Cedrela toona*. *D. latifolia* shows more promise when sown at the same stake as teak than when mixed in strips.

Terminalia myriocarpa — *Lagerstroemia flos-reginae* — **Indian Forest Service 1934**
Ended in pure crops of the faster growing *T. myriocarpa*.

Lagerstroemia flos-reginae — *Mesua ferrea* — **Indian Forest Service 1934**
More promising than the combination above. *M. ferrea*, a shade bearer is the underwood species.

Dalbergia sissoo — Eucalyptus spp., Morus nigra — **Indian Forest Service 1934**
An irrigated plantation in Punjab. Great losses of *M. nigra* due to frost.

Tectona grandis	*Melocanna bambusoides*	**Indian Forest Service 1934**
"	*Cephalostachyum pergracile*	
"	*Gmelina arborea*	
"	*Xylia dolabriformis*	
"	*Acacia catechu*	
"	*Dalbergia sissoo, Acacia catechu*	
"	*Dalbergia latifolia*	
"	*Pterocarpus marsupium*	
"	*Pterocarpus dahlbergioides*	
"	*Artocarpus hirsuta*	
"	*Swietenia macrophylla*	
"	*Bambusa tulda*	

Mixtures of *M. bambusoides* and Teak seem to have been successful from the economic point of view in the Chittagong Hill Tract. This may also be true for mixtures with *C. pergracile*. For *T. grandis* and *G. arborea* there are reports of both species suppressing each other. From the insect attack point of view the mixture is undesirable. *X. dolabriformis* is usually outgrown by the teak. Mixtures with *A. catechu* tend to separate into pure groups. Intimate mixture of *T. grandis, A. catechu* and *D. sissoo* has been tried. This has led to a mixture of *T. grandis* and *D. sissoo,* which is reported to have done well, though there are also reports of the opposite. Mixture with *D. latifolia* have not been successful, mainly due to browsing. Experiences of mixing with *P. marsupium* are discouraging. There are reports of mixture with *A. hirsuta* being silviculturally successful. From the economic point of view the mixture is regarded as questionable. Reports regarding mixture with *P. dahlbergioides* indicate that one species is likely to suppress the other. Mixed crops with *S. macrophylla* are regarded as failures, *S. macrophylla* being suppressed on good soils and vice versa. Mixtures with *B. tulda* have led to suppression of the teak.

Bombax malabricum — *Acacia catechu* — **Indian Forest Service 1934**
This seems to be a worthwhile mixture from the economic point of view.

Dipterocarpus turbinatus — *Gmelina arborea* — **Indian Forest Service 1934**
G. arborea was to serve as a nurse crop. The *Gmelina* must be thinned before they reach saleable size. Silviculturally, this mixture has not been a failure. Alternate strip mixtures are reported to have been successful.

Dipterocarpus turbinatus — *Tephrosia candida* — **Indian Forest Service 1934**
T. candida is to be the nurse crop. The mixture is reported to have been more successful than that with *Gmelina arborea*.

Acacia auriculiformis)
A. campylacantha)
Gmelina arborea) Bamboo — **Ram Prasad & Camire 1988**
Hybrid Eucalyptus)
Pongamia pinnata)
all showed rather better growth with bamboo.
Albizia procera showed rather worse growth with bamboo.

Cinamomum zeylanicum — *Tectona grandis* — **Streets 1962**

Dalbergia sissoo in mixture with various indigenous species. — **Streets 1962**

Eucalyptus globulus — *Acacia mearnsii* — **Samraj et al 1977**

Shorea robusta — *Grevillea pteridifolia*, *Eucalyptus camaldulensis*, *Toona ciliata*, *Pinus kesiya* — **Ram Prasad 1988**

Swietenia macrophylla — *Tectona grandis* — **Streets 1962**
tried between 1879 & 1896, but abandoned because of *Hypsipyla* and deer damage.

- **Malabar**

Swietenia macrophylla	*Tectona grandis*	Streets **1962**

planted under 30 to 40 year old *T.grandis* at the final thinning.

Terminalia arjuna with	*Casuarina equisetifolia*	Streets **1962**

- **N.Bengal**

Xylia dolobriformis	*Tectona grandis*	**Lahiri 1987**
also *Schima wallichii*		
Chukrasia tabularis		
Michaelia champaca		

Leucaena leucocephala	*Acacia nilotica*	**Bhatia & Kapoor 1984**

Positive effects of the mixture were detected.

INDONESIA

Pinus spp.	*Pittospermium monticolum*	**Alphen de Veer 1950b**
"	*Schima walichii*	
"	*Tarema incerta*	
"	*Eugenia spp.*	
"	*Quercus spp.*	
"	*Leucosyke spp.*	

The broadleaves were recommended to form an understorey in conifer plantations established to support a pulpmill. More than one mixing species should be used.

Altingia excelsa	*Castanopsis tungurrest*	Bakhoven **1930**
"	*Castanopsis javanica*	
"	*Podocarpus imbricata*	

Recommendations for establishment of non-teak plantations in the mountains.

Swietenia macrophylla	*Tectona grandis*	Becking **1928**

Tectona grandis	*Leucaena glauca*	Becking **1928**

Positive effects are mentioned.

Tectona grandis	*Schleichera oleosa*	**Deventer 1913**

Recommendation for establishment of mixed teak forests.

Tectona grandis	*Leucaena glauca*	Eidmann **1932**
"	*Antidesma bunius*	
"	*Pterocarpus indiensis*	
"	*Schoutenia ovata*	
"	*Cinnamomum iners*	
"	*Gluta renghas*	
"	*Eugenia subglauca*	
"	*Swietenia macrophylla*	
"	*Dalbergia latifolia*	

Investigation of underplanting. *L. glauca* is found suitable for this. *D. latifolia* may be even better suited.

Cupressus spp.	*Myrica javanica*	**Harencarspel 1908**
or	*Wenlandia rufescens*	
Casuarina spp.	*Wenlandia junghuniana*	
	Pittosporum ferrugine	

	Glochidion varium	
	Albizia falcataria	

Individual mixtures with either *Cupressus* or *Casuarina* species. Group mixing with species that will not grow tall is preferred to individual mixing.

Tectona grandis	*Leucaena glauca*	**Hart 1930b**

Mixing is favourable only under special circumstances.

Santalum album	*Leucaena glauca*	Kramer **1925**

Once the *S. album* roots reached the *Leucaena,* they developed well.

Tectona grandis	*Leucaena glauca*	**Kunst 1918**

If fires are avoided, mixtures develop vigorously.
Natural mixing is easier and better than artificial.

Diospyros celebica	*Tectona grandis*	**Alrasjid 1985**

Swietenia macrophylla)		Siregar **et al 1986**
Aleurites moluccana)		
Spathodea campanulata)		
Lagerstroemia speciosa)	*Melaleuca leucodendron*	
Durio zibenthinus)		
Artocarpus heterophyllus)		
Leucaena leucocephala)		

All failures ?*M. leucodendron* allelopathy

KENYA

Cupressus lusitanica	*Dombeya* (?*goetzenii*)	Streets **1962**
	Grevillea robusta	Graham **1949**

competes on equal terms to age 15, but has to be thinned heavily because of spreading crown causing butt sweep in the Cypress.

MALAYSIA (West)

Flindersia brayleyana in tall secondary forest		Streets **1962**
Swietenia macrophylla	*Gmelina arborea*	**Streets 1962**
Swietenia macrophylla	*Albizia falcataria*	**Streets 1962**
Teak	*Leucaena leucocephala*	**Ng et al 1982**
Araucaria hunsteinii	" "	

Shows some promise for controlling *Imperata* on more fertile sites.

MYANMAR

Tectona grandis	*Pterocarpus macrocarpus*	**Streets 1962**

NEPAL

Schima wallichii	*Pinus roxburghii*	Gilmour **et al 1990**

and other indigenous broadleaved trees by natural regeneration.

NEW CALEDONIA

Agathis lanceolata	*Acacia mearnsii*	**CTFT 1990**
"	*Albizia falcataria*	
"	*Herb plants*	
"	*Broadleaved trees*	

Experiment established in 1978. In the shade of *Albizia* or *Acacia, Agathis* grows well.

Agathis moorei	*Acacia mangium*	**CTFT 1991**
"	*Albizia falcataria*	
"	*Casuarina equisetifolia*	
"	*Leucaena leucocephala*	

Experiment established in 1981. The high mortality and poor growth of *A. moorei* is thought to be due to the soil.

Santalum austrocaledonicum	*Pinus caribaea*	**CTFT 1991**
"	*Arillastrum gummiferum*	
"	*Araucaria excelsea*	
"	*Araucaria luxurians*	
"	*Leucaena leucocephala*	
"	*Dalbergia sissoo*	
"	*Albizia falcataria*	
"	*Acacia auriculiformis*	
"	*Khaya senegalensis*	
"	*Tipuana tipu*	
"	*Acacia spirorbis*	
"	*Albizia lebbeck*	
"	*Casuarina equisetifolia*	
"	*Casuarina deplancheana*	
"	*Casuarina stricta*	
"	*Agathis ovata*	

Experiment established in 1980. Good results were achieved with *Albizia falcataria, Khaya senegalensis, Acacia spirorbis, Albizia lebbeck* and *Casuarina spp*. Poor results with *Pinus caribaea* and *Araucaria spp*.

Agathis lanceolata	*Albizia falcataria*	**CTFT 1991**

Experiment established in 1986.

Araucaria subulata	*Albizia falcataria*	**CTFT 1991**

Experiment established in 1986.

NIGER

Acacia tortilis **CTFT 1991**
Acacia nilotica
Balanites aegyptiaca
Anogeissus leiocarpus
Dalbergia sissoo
Experiment established in 1984. 8 plots of 25 trees, 5 of each species, randomly planted.

NIGERIA

Azidarachta indica	*Crotolaria striata*	MacGregor **1934**

4 months ht growth cut by nearly 50% in mixture from 4.04m to 2.4m

Chlorophora excelsa	Teak	**MacGregor 1934**
Cola cordifolia	Teak	**MacGregor 1934**
suppressed, but healthy & 80% survival; introduced to modify adverse effect on the soil.		
Erythrophleum ivorense	*Nauclea diderrichii*	**Henry 1960**
Not a success.		
Khaya grandifoliola	Teak	**MacGregor 1934**
At age 20 well above teak (21 m) - a good mixture.		
K.grandifoliola	*Triplochiton scleroxylon*	**MacGregor 1934**
overtopped by *T.scleroxylon* which will have to be thinned.		
K.senegalensis	*Dalbergia sissoo*	**MacGregor 1934**
fungal attack on *D.sissoo*		
K.senegalensis	Teak	**MacGregor 1934**
heavy borer damage in the *Khaya*.		
Lophira alata	Teak	**Henry 1960**
Not a success.		
Mansonia altissima	*Crotolaria striata*	**MacGregor 1934**
Mitragyna ciliata in any mixture only a success in low lying areas.		**Henry 1960**
Tectona grandis with	*Cassia siamea*	**Streets 1962**

PHILIPPINES

Tectona grandis	*Leucaena leucocephala*	**Granert & Cadampog 1980**
Swietenia macrophylla	*L.leucocephala*	

SENEGAL

Eucalyptus camaldulensis	*Acacia holosericea*	**CTFT 1991**
"	*Albizia lebbek*	
"	*Anacardium occidentale*	
"	*Azadirachta indica*	
"	*Cassia siamea*	
"	*Casuarina equisetifolia*	
"	*Prosopis chilensis*	

Experiment established in 1979. The only combination with normal growth is that between *E. camaldulensis* and *A. indica.*

SOLOMON ISLANDS

Swietenia macrophylla	*Securinega flexuosa*	**Solomon Islands 1988b**
1988 experiment - promising.		
	Leucaena leucocephala	
form of *S. macrophylla* thought to be superior, but *L.leucocephala* prone to attacks from *Phellinus noxius* and *Heteropsylla cubana*.		

Terminalia calamansanai
T.calamansanai has too spreading and vigorous a crown.
The following are not recorded as having been tried but were considered unsuitable - crowns too spreading - *Paraserianthes falcataria, Anthocephalus chinensis*

SRI LANKA

Swietenia macrophylla	*Artocarpus integrifolius*	**Streets 1962**
Swietenia macrophylla	*Tectona grandis* *Artocarpus integrifolius*	**Muttiah 1965**

TAIWAN

Taiwania cryptomerioides *Paulownia taiwania*	in mixture	**Un et al 1979**

TANZANIA

Cinamomum camphora	*Juniperus procera*	**Streets 1962**

TRINIDAD

Tectona grandis	*Copaifera officinalis* *Cedrela mexicana* *Cordia alliodora*	**Bell 1973**

all of which tended to be shaded out by the teak
Hyronima caribaea
Tabebuia serratifolia
Byrsonima spicata
Terminalia obovata
natural regeneration normally slashed in cultural operations.

UGANDA

Chlorophora excelsa	Eucalyptus	Dawkins **1949**

satisfactory when *C.excelsa* near drains (malarial control sites).
Cassia siamea
too much root competition.
Vernonia amygdalina
Does not shade out grass; no economic value.
Harungana madagascariensis
drought sensitive.
Markhamia platycalyx
poor at shading out grass, but economically useful.

The following were considered to be failures for unspecified reasons
Artocarpus sp)
Canarium schweinfurthii)
Ceara rubber)
Clausena anisata)
Cassia bicapsularis)

	Euphorbia tirucalli *Ficus* spp *Toona serrata* *T.ciliata*	
Chlorophora excelsa & *Khaya grandifoliola* has worked well on "better" sites	*Phyllanthus discoideus* & *Gmelina arborea*	
Chlorophora excelsa	Eucalyptus	**Streets 1962**

Mixtures recorded, apart from the data bank, during a visit to CTFT, Nogent sur Marne, in 1991.

Mixture	Country	Period
Acacia auriculiformis/ Eucalyptus camaldulensis	Benin	1986
Acacia auriculiformis/ Leucaena leucocephala	Benin	1986
Eucalyptus tereticornis/ Eucalyptus torreliana	Benin	1986
Eucalyptus tereticornis/ Eucalyptus camaldulensis	Benin	1986
Eucalyptus tereticornis/ Leucaena leucocephala	Benin	1986
Acacia auriculiformis/ Eucalyptus torreliana	Benin	1986
Tectona grandis/ Acacia maconochieana	Benin	1988-1989
Tectona grandis/ Acacia tenuissima	Benin	1988-1989
Tectona grandis/ Acacia tumida	Benin	1988-1989
Tectona grandis/ Anogeissus leiocarpus	Benin	1988-1989
Tectona grandis/ Azadiracta indica	Benin	1988-1989
Tectona grandis/ Cedrela odorata	Benin	1988-1989
Tectona grandis/ Chlorophora excelsa	Benin	1988-1989

Tectona grandis/ Khaya grandifolia	Benin	1988-1989
Tectona grandis/ Khaya senegalensis	Benin	1988-1989
Tectona grandis/ Terminalia ivorensis	Benin	1988-1989
Tectona grandis/ Terminalia superba	Benin	1988-1989
Khaya senegalensis/ Holoptelea grandis	Benin	1988-1989
Khaya grandifolia/ Holoptelea grandis	Benin	1988-1989
Diospyros mespiliformis/ Gmelina arborea	Benin	1988-1989
Chlorophora excelsa/ Afzelia africana	Benin	1988-1989
Afzelia africana/ Acacia amliceps	Benin	1988-1989
Pinus patula/ Callitris spp.	Burundi	
Khaya senegalensis/ Dalbergia sissoo	Cameroon	1984-1986
Acacia senegalensis/ Khaya senegalensis/ Azadirachta indica	Cameroon	1987
Schizolobium parahybum/ Cordia alliodora	Ecuador	1977
Tarrieta utilis/ Khaya ivorensis	Côte d'Ivoire	1926-1960
Triplochyton scleroxylon/ Khaya ivorensis	Côte d'Ivoire	1961-1964
Triplochyton scleroxylon/ Tieghemilla heckelii	Côte d'Ivoire	1961-1964
Triplochyton scleroxylon/ Gmelina spp.	Côte d'Ivoire	1961-1964
Triplochyton scleroxylon/ Terminalia superba	Côte d'Ivoire	1961-1964
Triplochyton scleroxylon/ Tectona grandis	Côte d'Ivoire	1961-1964

Acacia mangium/ Acacia auriculiformis	Côte d'Ivoire	1985-1988
Terminalia superba/ Terminalia ivorensis	Côte d'Ivoire	1985-1989
Terminalia superba/ Tectona grandis	Côte d'Ivoire	1985-1989
Eucalyptus camaldulensis/ Indigofera teysmannii	Madagascar	1951-
Eucalyptus camaldulensis/ Cassia siamea	Madagascar	1951-
Eucalyptus camaldulensis/ Acacia cyanophylla	Madagascar	1951-
Eucalyptus microtheca/ Indigofera teysmannii	Madagascar	1951-
Eucalyptus robusta/ Acacia mangium	Madagascar	1988
Lophira alata/ Swietenia macrophylla	Nigeria	1918-1939
Lophira alata/ Tectona grandis	Nigeria	1918-1939
Tectona grandis/ Lophira alata	Nigeria	1949-1960
Tectona grandis/ Nauclea diderrichii	Nigeria	1949-1960
Tectona grandis/ Lovoa trichilioides	Nigeria	1949-1960
Tectona grandis/ Swietenia macrophylla	Nigeria	1949-1960
Erythrophleum ivorense/ Nauclea diderrichii	Nigeria	1949-1960
Nauclea diderrichii/ Khaya ivorensis	Nigeria	1949-1960
Nauclea diderrichii/ Lovoa trichilioides	Nigeria	1949-1960
Nauclea diderrichii/ Entandrophragma angolense	Nigeria	1949-1960
Nauclea diderrichii/ Entandrophragma cylindricum	Nigeria	1949-1960

Lovoa trichilioides/ Khaya ivorensis	Nigeria	1949-1960
Acacia melanoxylon/ Pinus radiata	Rwanda	
Eucalyptus camaldulensis (microtheca)/ Prosopis juliflora	Senegal	
Eucalyptus camaldulensis (microtheca)/ Acacia holoserica	Senegal	
Eucalyptus spp./ Gmelina arborea	Senegal	1983
Tectona grandis/ Leucaeana glauca	Togo	1910
Tectona grandis/ Khaya senegalensis	Togo	1910
Tectona grandis/ Cassia siamea	Togo	1910
Tectona grandis/ Albizzia zygia	Togo	1910
Tectona grandis/ Erythrophleum guinensii	Togo	1910
Acacia mangium/ Eucalyptus tereticornis	Togo	1982-1988
Acacia auricliformis/ Eucalyptus torreliana	Togo	1982-1988
Eucalyptus tereticornis/ Eucalyptus torreliana	Togo	1988
Eucalyptus saligna/ Markhamia platycalyx	Uganda	1918-1930
Eucalyptus robusta/ Grevillea robusta	Uganda	1960-1965
Eucalyptus robusta/ Cupressus lusitanica	Uganda	1960-1965
Eucalyptus robusta/ Eucalyptus spp.	Uganda	1960-1965
Eucalyptus robusta/ Toona ciliata	Uganda	1960-1965

Aucoumea klaineana/ Cassia siamea	Zaire	1942-1943
Haronga paniculata/ Smithia bequaerti	Zaire	Before 1953
Haronga paniculata/ Dodonea viscosa	Zaire	Before 1953
Haronga paniculata/ Sesbania spp.	Zaire	Before 1953
Eucalyptus spp./ Bridelia ferruginea	Zaire	Before 1953
Eucalyptus spp./ Bridelia micrantha	Zaire	Before 1953
Smithia bequaerti/ Bridelia ferruginea	Zaire	Before 1953
Smithia bequaerti/ Sakersia laurentii	Zaire	Before 1953
Smithia bequaerti/ Myrica salicifolia	Zaire	Before 1953
Smithia bequaerti/ Lacnopylis spp.	Zaire	Before 1953
Smithia bequaerti/ Trema spp.	Zaire	Before 1953
Smithia bequaerti/ Markhamia spp.	Zaire	Before 1953
Dodonea spp./ Bridelia spp.	Zaire	Before 1953
Dodonea spp./ Trema	Zaire	Before 1953
Dodonea spp./ Haronga spp.	Zaire	Before 1953
Markhamia lutea/ Smithia spp.	Zaire	Before 1953
Markhamia lutea/ Dodonea spp.	Zaire	Before 1953

APPENDIX 4

SANDALWOOD

Members of the family Santalaceae are root hemi-parasites and, though they have been recorded as parasitising grasses and may on occasion exist without the benefit of a host, they are almost always associated with other trees and shrubs. Mixed planting has therefore been found to be essential in the establishment and management of sandalwood.

The genus *Santalum* occurs over a wide geographic area.

Australia (1) from Cape York to Victoria and through to West Australia	*S.spicatum, S.acuminatum, S.lanceolatum, S.murrayanum, S.obtusifolium.* (4)
New Guinea (1)	*S.macgregori*
New Caledonia & Vanuatu (1)	*S.austrocaledonicum*
Fiji (1)	*S.yasi*
Tonga (4)	*S.yasi*
Hawaii (3)	*S.elipticum, S.freycinetianum S.haleakalae, S.paniculatum*
Tahiti, Marquesas, Henderson **Island Austral Islands, Cook Islands, Society Islands** (4)	*S.insulare*
East Indonesia (1)(now almost entirely confined to West Timor)	*S.album*
India (2) (primarily on the Deccan plateau of Karnataka & Tamil Nadu, but found throughout India)	*S.album*
Juan Fernandez (4)	*S.fernandezianum* (extinct)

(1) McKinnell (1990)
(2) Rai (1990)
(3) Hirano (1990)
(4) Applegate et al (1990)

The highest grade logs are used for carving and *S.album* produces the highest quality logs, because it is close grained and has a high oil content; prices up to US$ 9,400 per ton can be obtained in India. Lower grade logs go to the incense market at a price varying from US$ 2,000 to US$ 5,000 per ton, though roots and butts of *S.spicatum* and *S.album*, which have a higher oil content, may fetch up to US$ 7,000 per ton. Australia supplies most of the world incense market through Hong Kong and Taiwan. Wood chips and powdered wood command prices of around US$ 2,300 per ton. Sandalwood oil is chiefly produced in India, where 1 ton of *S.album* heartwood can produce 60 kg of oil, the export price of which starts at US$ 1,500 per kg. The market for oil is primarily for perfumeries in France and New York (Applegate et al. 1990).

Yields of heartwood oil **vary** with the species (McKinnell 1990).

5 - 7%	*S.album* and *S.yasi*
3 - 6%	*S.austrocaledonicum*
2%	*S.spicatum*

S.album has a wood density of 930 - 950 kg/m^3.

The yield of oil from some species such as *S.acuminatum* and *S.lanceolatum* found in Australia are so low that oil is not usually distilled from these species (McKinnell 1990).

S.album is the most valuable species. It has been exploited for many centuries in India, West Timor, Sumba and Flores in Indonesia and it is now being introduced into many countries (e.g. Hawaii (Hirano 1990), Java and Bali (Applegate et al 1990), West Australia (McKinnell 1990)). It has been suggested that *S.album* is an introduced tree in India, but that theory has been rejected on the grounds that the tree is so deeply involved in Indian literature, ethos and culture (Rai 1990).

There are records of sandalwood use in India 4,000 years ago (Rai 1990) and 1,500 years ago in Hawaii (Merlin and Ravenswaay 1990), but exploitation increased immensely with the exploration of the Pacific by the West in the 18th century. By about 1870 there was virtually none left on many of the Pacific Islands and only recently have measures been introduced to regulate exploitation of sandalwood in order to conserve it. Although the stocking of *S.spicatum* in West Australia is low (2/ha) the area over which it grows is so large that, despite largely unregulated cutting in the last century and the beginning of the 20th century, large volumes are still available. The history of sandalwood exploitation in Western Australia (Statham 1990) gives a good idea of the fluctuations of the trade. Exports of *S.spicatum* started in 1843 and rose as high as 9,600 tons in some years at the end of the 19th and beginning of the 20th century. From the early 1920s, when up to 14,300 tons a year were exported, exports fell to about 1,000 tons a year in the late 1930s. During the Second World War exports ceased, but have now built up to about 1,800 tons a year with an export value of A$ 11.5 million in 1989. Exploitation is now carefully regulated, but nevertheless it has been estimated that natural stocks will only last about another sixty years (McKinnell 1990). Currently about half the sandalwood harvest is dead wood, but the practice of exploiting the whole tree, including the butt and roots, which have the highest oil content, continues (McKinnell 1990). As recently as 1954 a Forests Department report stated that the results generally from experimental work did *not* warrant any attempt to grow sandalwood on a large scale (Statham 1990), but nevertheless "pullers" were encouraged to replace trees with sandalwood nuts. More recently the Sandalwood Research Institute has been investigating the possibility of introducing *S.album* which it is expected will have a rotation of 30 years as against 60 to 80 years for *S.spicatum*; these trials are promising (McKinnell 1990).

Santalum spp. can grow on a wide range of soils, in temperatures of 0°C to 40°C and rainfall from 500 mm to 3,000 mm (Neil 1990). In India it is considered to be a tree of dry deciduous forests and when a site becomes mesic sandalwood retreats to drier sites, but sandalwood is fire tender (Rai 1990). In Queensland it has been noted that it occurs in open woodlands, but tends to be more common on the outer edge of scrubs of *Melaleuca acacioides* and *Excoecaria parvifolia* (gutta percha) around drainage lines. On these sites, at the interface of the *M.acacioides* scrub and the open woodland, the grass is sparse and hot fires which are common in the densely grassed open woodland do not occur (Applegate et al 1990b). In Western Australia it grows on sites receiving little rain and regeneration appears to be dependent on a succession of wet years.

Sandalwood is a root hemiparasite that is known to parasitise at least 300 species of plants, ranging from grasses to trees; it has also been known to parasitise other sandalwood trees (Rai 1990). It attaches itself to its host by haustoria and appears to obtain N, P and basic amino-acids from the host while obtaining Ca and K from the soil (Neil 1990). No reference was found to its effect on the host, but it does not appear to be debilitating. In fact the host tree has to be carefully chosen not to be so vigorous as to suppress the sandalwood.

When sandalwood is raised in nurseries the seedling should be allowed to attach itself to host and this is achieved by raising the sandalwood and host in the same pot (Neil 1990, Rai 1990). But in Western Australia this technique is considered to be only a research tool and the risk of rupturing the sandalwood-host connection in planting out is too high for commercial planting; for commercial planting direct seeding is advocated, but only with the expectation of getting 1% of the seed through to a tree (McKinnell 1990). In India a hollowed bamboo is used for direct seeding into thickets (Rai 1990). Despite the observation from West Australia several countries have found that a dual host system produces the best results when raising sandalwood artificially. At the nursery stage a primary host is used and this should be a low growing, short-lived shrub; *Cajanus cajan* in India (Rai 1990), *Sesbania grandiflora, Breynia cerrua, Amaranthus* spp., *Medicago* spp. and tomato, *Calotropis, Capsicum* in Timor (Neil 1990; McKinnell 1990), *Alternanthera sessilis* in Vanuatu (Bule and Daruhl 1990), *Gastrolobium microcarpum* and *Acacia pulchella* in Western Australia wheat belt and *Atriplex rhagodioides, Cratystylis subspinescens* and *Mariana polysterygia* in the arid zone (McKinnell 1990). *M.polysterygia* is considered a particularly good host because it is thorny and gives protection against browsing to which sandalwood is particularly susceptible. On planting the sandalwood into the field the seedling should be established near a perennial secondary host; this is usually achieved by planting the sandalwood and primary host in alternate rows with a secondary host at two to three metre spacing (Rai 1990). Secondary species recommended include *Albizia* spp., Acacias (particularly *A.nilotica*) and other legumes such as *Bauhinia biloba, Dalbergia sissoo* also *Terminalia* spp. in India (Neil 1990); *Casuarina equisetifolia, Pongamia pinnata, Melia azedarach, Wrightia tinctoria* and *Cassia siamea* (Rai 1990), but *Cassia fistula* and *Acacia auriculiformis* are considered indifferent hosts (Ananthia et al 1988); *Albizia falcataria, A.lebbek, Acacia spirorbis, Dalbergia* spp., *Casuarina* spp. and *Khaya senegalensis* are recommended in New Caledonia, but *Pinus caribaea* and *Araucaria* spp. gave poor results (CTFT 1991); *Acacia acuminata* and *A.aneura* give good results in Western Australia (McKinnell 1990).

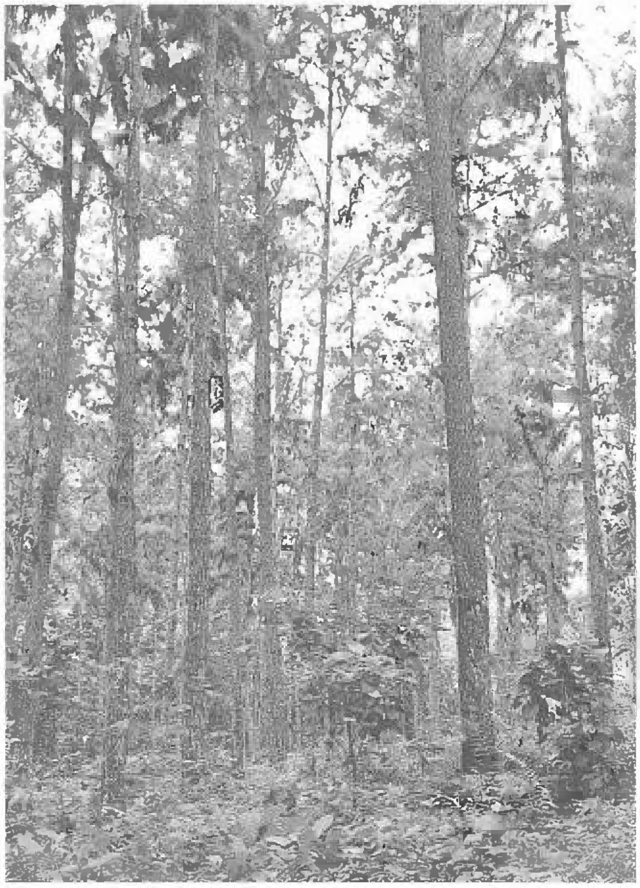
1. Coppice regrowth of pure *Eucalyptus globulus* on stumps planted in 1863. No undergrowth despite open stand. Tamil Nadu, India. CSIRO

2. *Acacia mearnsii* (wattle) in Kenya. Industrial plantation for tannin, charcoal, poles and fuelwood. Close spacing, little undergrowth. CSIRO

3. Mixture of *Tarrieta utilis* and *Khaya* sp. (25 years) at Yapo, Côte d'Ivoire. CTFT

4. Pure *Terminalia superba* (8 years). Although fairly closely grown, the undergrowth has developed. Tene, Côte d'Ivoire. CTFT

5. Pure *Maesopsis eminii* (19 years). A vigorous understorey has developed beneath this lightly-crowned and open grown stand. Anguededou, Côte d'Ivoire. CTFT



6. Pure *Pinus caribaea* (22 years). Regular thinning has allowed the development of a dense undergrowth. Yapo, Côte d'Ivoire. CTFT

7. A young mixture of teak and *Terminalia superba* (3 years). Tene, Côte d'Ivoire. CTFT

8. Pure teak (c. 12 years), Navagotha, Sri Lanka. No undergrowth; the fallen leaves are fuel for fires in dry weather. F. Ng

9. Mixture of Teak, *Swietenia macrophylla* and *Artocarpus heterophyllus* (c. 80 years). Sundapola, Sri Lanka. F. Ng

10. Mahogany regeneration, which will tend to dominate the species composition of this mixed plantation. Sundapola, Sri Lanka. F.Ng